University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4028

Project Final Report (PFR)

Weather-Balloon Infrared Readings of Moisture in Soil
(WIRMS)

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Information

Project Customer

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1. Project Purpose

Marisa Exnicious, Sam Shaver

Soil moisture content is a crucial aspect of crop management systems. The over-watering of crops increases the environmental impact of agriculture, while under-watering inhibits the growth and health of crops. The WIRMS project will address these problems by building a non-intrusive solution to provide IR data that can be used to monitor soil moisture content over a large area for an extended period of time.

Existing solutions such as in-ground measurement systems, satellite based systems, and UAS drones have attempted to provide similar data, but have fallen short in a few key areas. Various in-ground measurement techniques are discussed in a paper first published in 1962 by the Department of the Interior. The main in-ground measurement technique discussed, the gravimetric method, measures moisture content in a sample of soil by weighing the sample before and after drying it[2]. Additionally, the radioactive method and several other techniques were described and detailed in this paper, including electrical-resistance, heat-diffusion, absorption, tensiometric, and penetration. While some of these methods provide accurate measurements with good spatial resolution, they are all highly intrusive, and would require some sort of disruption to crop growth if used in-situ on a farm. Additionally, such in-ground measurement techniques are only feasible for short durations and as such do not provide the level of temporal accuracy required.

Likewise, satellite and UAS drones have been found to be viable options for moisture detection[4] but both are lacking in key areas. Satellites provide data for large portions of the United States, but this data is not suitable for individual farmers. Drones aim to combat this problem by imaging smaller areas. However, these areas are still too large for individual farmers and cannot be used for persistent passive measurements as a licensed pilot must be present at all times.

The WIRMS project combats the issues of the above solutions while maintaining many of their benefits. Through the use of a tethered weather balloon and a near infrared camera (NIR), data will be captured non-intrusively with a cadence of 10 minutes. Data will be downlinked in real time, allowing a farmer to actively react to the needs of the crops. The simplicity of the system will allow for quick set-up, take-down times, and simple transportation. Furthermore, WIRMS will be capable of flight times that enable farmers to observe how different environmental factors impact their crops over time.

2. Project Objectives and Functional Requirements

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2.1. Levels of Success

In order to fulfill the aforementioned project purpose, levels of success are introduced to further specify and partition project objectives. Levels of success range in complexity from level one to level three where level one signifies the most basic criteria for success. These objectives must be met in order to produce a functioning, baseline system. Level two success criteria add complexity to the level one tier and level three successes are the most difficult or complex items WIRMS aim to achieve. The mission will still function and be considered somewhat successful even if level three objectives are not met. All levels of success should be met to fulfill the product specifications desired by ASTRA.

Objectives for success are separated into two categories: Structural & Instrument and Software & Electronics. WIRMS has a broad mission and each aspect must be well executed for the project to be successful. Each subsystem has been simplified to limit the possibility of component or interface failure. The boxes highlighted in green are the highest levels of success met for each subsystem. All levels of success lower than the level highlighted in green were also met. The only levels of success not met were three level threes having to do with foreign object identification and data extrapolation past the testing period.

STRUCTURAL AND INSTRUMENT

	Ground Structure	Instrumentation	Airborne Structure	General Structures
Level 1	Reference points for image calibration are visible under operational conditions. Sensitive components of ground structure are weather resistant.	Images taken have a resolution of 7” x 7” per pixel for an on-ground footprint. Imaging instrumentation operates for 80% of flight duration.	Airborne structure is capable of a continuous flight time of 1 hour. Airborne structure capable of safely deploying to flight altitude and retracting from flight altitude.	Deployment and retraction of the entire system must be completed in under 24 man-hours with each component weighing under 55 lbs.
Level 2	Reference points are visible during all times of the day and night.	Imaging instrument can image an area of 300 square feet.	Airborne structure is capable of a continuous flight time of 1 day.	Inclement weather does not damage sensitive components.
Level 3	Ground structure does not incur damage under inclement weather conditions.	Imaging instrument is able to detect near IR wavelengths of light.	Airborne structure is capable of a continuous flight time of 1 week (by analysis).	

SOFTWARE AND ELECTRONICS

	Capture Software	Data Processing/Analysis	Power	General Software	Communication
Level 1	Image capture is autonomous and occurs at 15 minute intervals during operational conditions. Environmental data capture is autonomous and occurs every minute.	Image packets are uniformly formatted (e.g. JPG) and event logs contain critical data (images taken, commands sent, etc.)	System has enough power (generated + reserve) to run for 1 hour.	Environmental data and images are properly timestamped.	A link allows all data to be transferred between the ground station and the instrument suite.
Level 2	Capture software is able to autonomously flag a collected image if environmental conditions are non-operational.	Data processing able to account for drift in image location based on reference points.	System has enough power (generated + reserve) to run for 1 day.	Exported data is in a cohesive, established, scientific format (e.g. netCDF, h5, CSV, etc.)	Data transfer to and storage on the ground station is autonomous.
Level 3		Data processing can create a quality flag to indicate if data has an anomaly (e.g. animal walks into frame).	System has enough power (generated + reserve) to run for 1 week by analysis.	Software does not require human intervention between set-up and tear-down.	A series of images collected in a burst can be downlinked without any data loss.

2.2. Concept Of Operations (CONOPS)

The concept of operations for project WIRMS shows how the entire system will be deployed and operate during its final data collection period. The final data collection will occur on a general purpose field of soil with minimal surface obstruction, most likely at CU's South Boulder campus. The ground station, balloon payload, and supporting equipment (guy wires, stakes, etc.) will be packaged into a housing that is no larger than 5' x 5' x 2' and transported via pickup truck to the testing location. After arriving, the packaged materials will be unloaded from the vehicle and removed from their housings.

A grid will be set up on the ground to assist team members with soil sample collection, soil moisture sensor placement, and placement of other ground system components. Soil samples will be collected and bagged from five predetermined locations within the target imaging area then soil moisture probes will be placed in those areas. Then structural setup can commence.

Three equal length guy wires will be secured to the airborne structure such that, at max elevation of 118ft, the wires will form a 45 degree angle relative to the ground. The wires will form a circular footprint on the ground. The payload containing the balloon, instrument suite, and airborne structure will float at the center of the testing area. The three guy wires will be attached to the airborne structure on one end and fed into worm winches at each ground structure; each ground structure will be weighted and staked into the ground. The ground station containing the ground processor/power supply and other sensors are placed at one of the ground structures so that a power and data cable can run up to the instrument suite alongside a structural tether.

Once all connections are made and ground structures are moored in place, the flight vehicle is filled with helium and the instrument suite is powered on. The team then winches the flight vehicle and instrument suite up to an altitude of 118 feet. The instrument suite will then collect environmental data every ten seconds and IR images every ten minutes. All captured data will be routed to the ground immediately after collection for storage.

At the end of the 24 hour (with 80% uptime) test duration, the balloon and instrument suite will be winched back down to the ground. The helium will be let out of the balloon then a final soil sample will be taken and labelled from the five previous sample locations. The system is then packed/stowed into the pickup truck and removed from the site.

Offsite, post-processing will packetize and organize all collected data, align the images, and perform any auxiliary data processing. The soil samples will be baked to determine soil moisture and data from the soil moisture probes collected during the test will be compiled. This process is illustrated in the following CONOPS diagram.

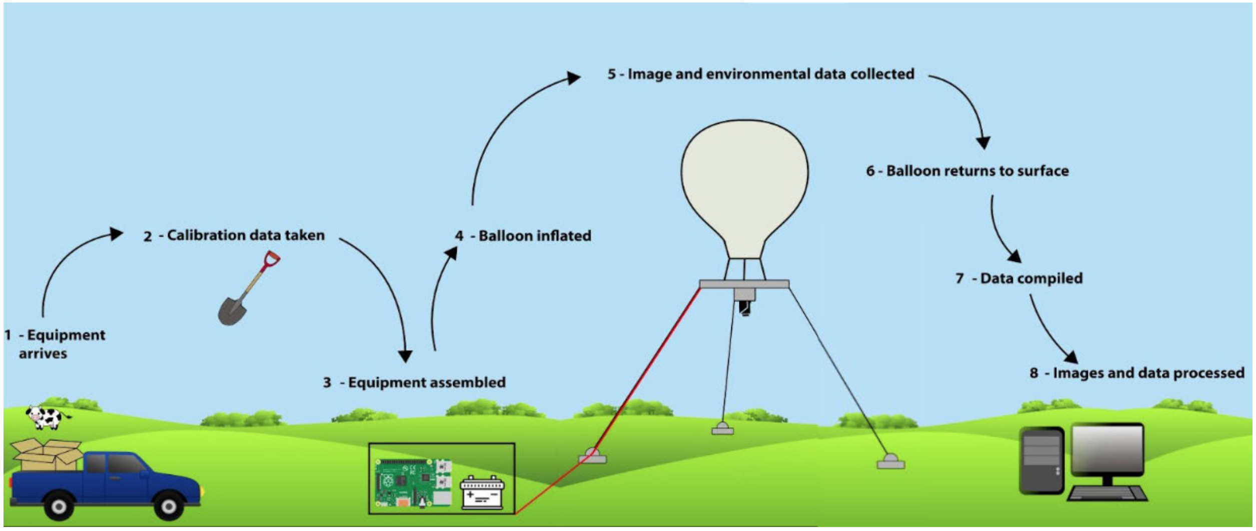

Figure 1: WIRMS CONOPS

2.3. Project Deliverables

At the end of the Spring 2020 semester, Team WIRMS was planning to deliver the final hardware, software, and collected data package to its customer. Along with the full system, documentation on how to use it will also be provided to the customer in the form of a user's guide. A summary of planned deliverables to the customer is listed in table 1 below. However given the circumstances, these deliverables have been modified from final versions to simply the latest versions as of project halt.

Table 1: Deliverables to Customer

Customer Deliverables

Deliverable	Content
Physical System	All physical components of the system
Software	Data collection, communications, image alignment & post-processing
End Data Package	Aligned IR images (location and time stamped), environmental data
Soil Moisture Calibration Data	Calibration data from in-lab and during flight soil moisture measurements
User's Guide	Instructions and specifications on using the system

In order to meet course objectives for ASEN 4018/4028, multiple reviews and documentations will be provided to the Professional Advisory Board (PAB). Fall reviews and documents have been completed and are shown in the upper portion of table 2. Reviews and documentation completed in the Spring are listed in the lower portion of the same table.

Table 2: Course Deliverables

ASEN 4018/4028 Deliverables

Deliverable (type)	Content	Date
PDD (written)	Problem Definition	September
CDD (written)	Baseline Design Selection	October
PDR (presentation)	Baseline Design Feasibility	November
CDR (presentation)	Final Design	December
FFR (written)	Entire Final Design	December
MSR (presentation)	Manufacturing Status	February
TRR (presentation)	Test Readiness	March
FOR (presentation)	Verification and Validation	March
PFR (presentation)	Public Symposium	April
	All documentation	April

2.4. Functional Block Diagram

A functional block diagram (FBD) of the full system gives some insight on how the system functions. Figure 2 shows how all of the major components interface to produce the IR data required.

As an overview, the system can be visualized in four different sections: The ground system (encapsulating every component on the ground including the power supply), data storage, structural support, and additional sensors. The ground system has three ground stations, which interface through Kevlar tethers with the airborne structure. Power is routed from one of the ground stations to the instrument suite through a cable and data can travel from the ground to the air or the air to the ground through another cable.

The Kevlar tethers provide a strong and relatively inelastic connection between the ground stations and the airborne structure, which acts as an interface between the balloon and the instrument suite. The balloon is inflated with helium such that there is an excess lift to counteract strong translational winds. In case the balloon becomes untethered, a rapid deflation device (required by FAA regulation) is situated on the balloon. As this circumstance is very unlikely, further explanation will be left to subsequent sections.

The airborne structure also houses the instrument suite which contains the key instrumentation for the project. A Raspberry Pi contains environmental sensors and processes data in the air. The IR imager is located in the instrument suite and is the most important piece of the system. Images and environmental data are time-stamped in the air then transmitted through the Ethernet cable to the ground structure for long-term storage. At the end of a testing period, the stored data can be transferred to a computer where image alignment and data packetization occurs.

In the following figure, components are grouped together into larger components and interfaces are shown through colored arrows. The colors of the arrows and boxes indicate the type of connection and the type of component respectively. The legend provides further information to interpret the FBD.

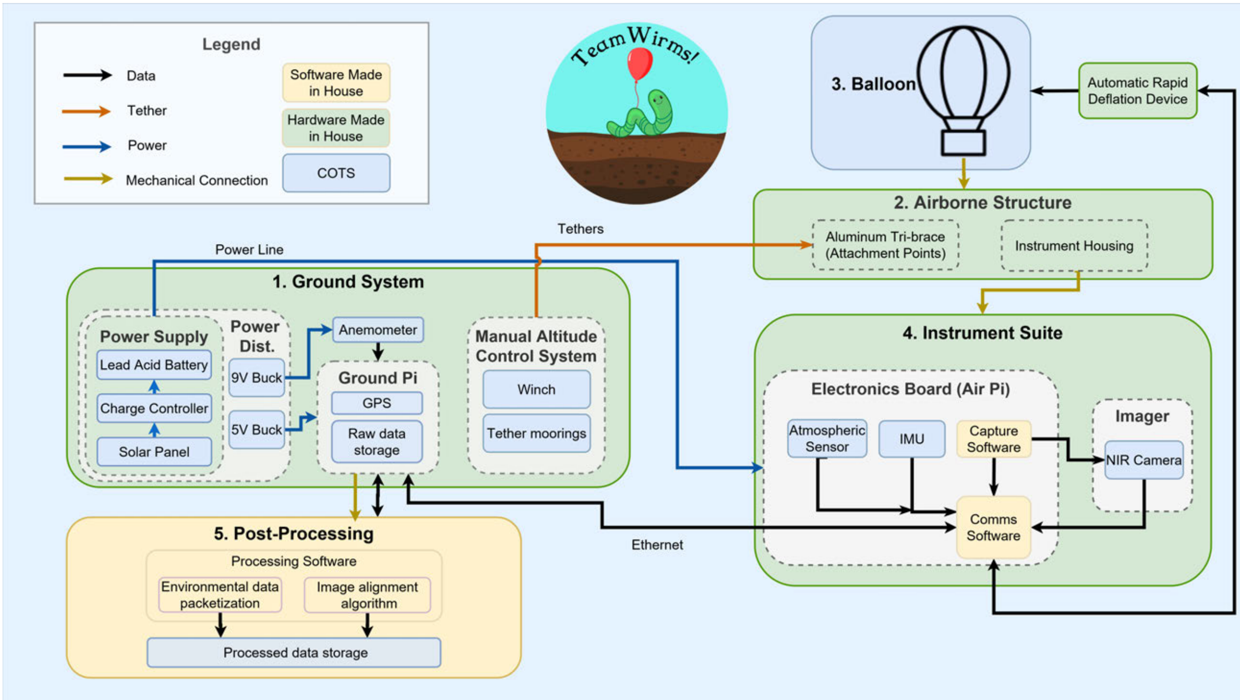

Figure 2: WIRMS FBD

The system described in the FBD has everything it needs to deliver useful IR data to the customer for use in their soil moisture algorithm. The instrument suite provides data as well as quality information based on IMU and atmospheric sensor output to meet level three success criteria and aid in diagnosing issues in images. An anemometer on the ground gives similar insight based off of wind speed. The design of the system allows WIRMS to collect data in a scalable and simple way for the benefit of ASTRA.

2.5. Functional Requirements

WIRMS has eleven functional requirements which are derived from mission success criteria and given by the customer. These high level requirements are listed in table 3 along with their importance or rationale as well as who/where the requirement was derived from.

Table 3: Functional Requirements, Rationale, and their Sources

ID	Requirement Text	Rationale	Source
FR1	The flight vehicle shall be deployable from the ground to an altitude between 100 - 150 ft.	The flight vehicle must carry the instrument suite to an altitude capable of imaging a large area of soil but must not surpass 150 ft altitude due to FAA regulation.	FAA and mission success criteria
FR2	The flight vehicle shall be capable of operating in the air for 1 day.	The system must operate and collect images for a day, with at least 80% of the flight being uptime.	Required by customer
FR3	The system shall be provided enough power to sustain a 1 day flight.	The system must receive continuous power to remain power positive and collecting images.	FR2 and mission success criteria
FR4	The imaging system shall be able to autonomously image with a resolution of 7x7 square inch per pixel for 80% of 1 day.	An autonomous system allows for limited occurance of human error. This resolution will provide higher fidelity data than any current solution for detecting soil moisture.	Required by customer
FR5	The instrument suite shall take and process environmental data for a day.	Environmental data must be provided to the customer to aid in soil moisture algorithm development and quality flagging images.	Required by customer and mission success criteria
FR6	Data shall be transferable from the instrument suite to the ground station.	The ground station must first receive data from the instrument suite to store it for the duration of the test.	Required to satisfy project objectives
FR7	Data shall be stored by the ground station and post-processed.	Test data is a deliverable to the customer and must be stored and organized into a useful format prior to delivery.	Required by customer and critical for mission success
FR8	The flight vehicle shall be retractable to the ground from an altitude between 100 and 150 ft.	The system (except the flight vehicle) must be reusable and must therefore be collectable at the end of the test period.	Required by customer and critical for mission success
FR9	Soil moisture calibration data and GPS data shall be collected.	Baseline data must be collected for the customer to compare IR information to. This is required in order for ASTRA to develop a soil moisture model with accurate location information.	Required by customer
FR10	The system shall comply with all ITAR requirements	The project must comply with ITAR requirements to be deployed and used.	Course driven, law driven
FR11	The flight vehicle shall comply with all FAA requirements	The project must comply with FAA requirements to be deployed and used.	Course driven, law driven

3. Design Process and Outcome

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3.1. Conceptual Design Alternatives

3.1.1. Flight Vehicle

The flight vehicle will serve as the means to lift the instrument suite to its desired camera defined altitude for proper data capture. The flight vehicle must conform to all FAA regulations applicable and be upscalable for future projects, i.e. increases in altitude, payload capacity, and endurance. Although the customer strongly recommended the use of a balloon to serve as the flight vehicle in their initial presentations, several other flight vehicle options were explored, see Appendix 10.2 for these comparisons.

3.1.2. Camera

A major component of the instrument suite is the camera. As stated above, the images taken will be used to build a soil moisture model that can characterize water content in soil. Previous research by Landsat 8[11] and various universities[8] identify short wave infrared (SWIR) and near infrared (NIR) bandwidths (0.85 -2.3 μm) as ideal for identifying soil moisture content. The absorption bands will be key in identifying the amount of soil and water present. Although other wavelengths may be useful, such as RF, the customer required IR and specifically asked us to refrain from using RF frequencies.

Infrared cameras focus infrared radiation through a lens onto a small light sensor. Just like an optical camera, the resolution of images depends on the sensor array. Typical array sizes span 320x256 to 1600x1200 pixels. Other important specifications to consider are the field of view, power draw, ease of integration, weight, and resilience. See Appendix 10.2.

3.1.3. Microcontroller

In order to facilitate the control of the on-board instrument suite and data transfer to the ground station, an onboard processor will be necessary. Due to the significant weight that complex processors (e.g. personal computers) have, only small, single-board microcontrollers were trade studied. While the complexity of microcontrollers can vary vastly, the learning curve to utilize extremely simple, lightweight microcontrollers (such as FPGA embedded systems) was deemed too steep for the scope of this project. As a result, only ”complex” microcontrollers were trade studied, where ”complex” is defined as a microcontroller that can be programmed using higher level programming languages. Given that the microcontroller is the interface between the data taken on the flight vehicle and the ground station, it is critical that the board is powerful and able to interface with inflowing and outflowing data communication methods (e.g. USB etc). See Appendix section 10.2.

3.1.4. Power Source

Providing enough power to the system is critical to the success of this project. Since this system will not be used in locations that have access to the power grid, the power required to operate the system must be stored within the ground structure. Since this system will be operating during the night, the need for batteries is clear. The chemical compound in a battery will be the main factor which then determines the price, energy density, and lifetime of a given battery. Lead acid, lithium polymer, lithium ion, and nickel metal-hydride batteries were the main options considered since they are some of the more readily available rechargeable batteries. Due to the duration of this mission, solar panels were also considered as a power source solution. See Appendix 10.2 for a detailed analysis of all options explored.

3.1.5. Communications

Communication between the ground station and flight vehicle will be necessary for sending start/stop commands, retrieving and storing science data, as well as monitoring the status of the flight vehicle. Because both tethered and untethered flight vehicles are being explored for this project, both wired and wireless communication methods were investigated. The communication system must interface with the microcontroller on both the flight vehicle and the ground station and be capable of transmitting large science packets (~800 Mbits) every 10 minutes along with smaller environmental data packets (~10 kbits) at the same cadence. To accomplish these tasks, five different communication methods were examined including Serial Peripheral Interface Bus (SPI), Power Over Ethernet (POE), Radio Communication, Wireless Local Access Network (WLAN), and RS-485. While there are many other communication methods available, these five have heritage, will fit within the flight vehicle, and will not consume exorbitant amounts of power. See section 10.2 for these comparisons.

3.1.6. Data Calibration

Since the eventual goal of this project is to determine the moisture content of the field being observed, additional moisture measurements will be taken in order to calibrate the IR images provided by instrument suite. By providing several data points of soil moisture that correspond spatially and temporally to the IR images taken, general statistical correlations between the IR intensities and water moisture can be extrapolated. While this group is not directly responsible for the translation/homography between IR and moisture content level, the data calibration method used will determine the accuracy and validity of the final moisture level data product. See Appendix 10.2 for pros and cons of each explored solution.

3.1.7. Tether Material

If it was determined that the mission requires the use of a tethered flight vehicle, support structures will be necessary to keep the flight vehicle at a constant altitude and position. There are several elements that make up the supporting structure for this system; the two most important of these being tether materials and mooring methods. Important aspects of the tether materials include breaking strength, weight, and durability. Important aspects of the mooring methods include ease of set-up and reliability. Since this system needs to be deployable/retractable in 24 man-hours, the only two temporary solutions for mooring are using weights, or stakes (permanent mooring such as concrete is not usable). Since there is such a high uncertainty associated with shear forces when using stakes in varying soil conditions, this option was not considered, leaving weights as the only choice for mooring. The options for tether materials will now be considered as follows in Appendix 10.2.

3.1.8. Environmental Sensors

During operational flight time, it is imperative that the instrument suite can measure the environmental conditions as well as the movement of the flight vehicle. The environmental conditions that will be measured are temperature, humidity, pressure, and windspeed. The environmental data will be paired with IR images so the data can be calibrated accordingly, and trends can be seen relating the IR soil moisture measurement to different environmental conditions. The environmental sensors also provide insight to possible storms and upcoming inclement weather conditions. The position and movement of the flight vehicle will be observed as well; altitude will be determined through GPS while an accelerometer and gyro will be present as an inertial measurement unit. The measurements from the IMU (inertial measurement unit) will determine whether or not the flight vehicle is stable, and warrant the use of IR data. The sensor suite choices below are strictly COTS devices due to the fact that they are inexpensive and simple to integrate, these are explored in detail in Appendix section 10.2.

3.1.9. Reference Points for Image Alignment

The team initially thought distinguishable reference points would be required on the ground in order to aide the image alignment algorithm. Through testing, the NIR camera did not perform any better with reference points so these were removed from the design. A discussion of the team's initial choices and analysis of pros and cons for choosing various reference points is found in appendix 10.2

3.1.10. Rapid Deflation Device

FAA and municipality laws dictate that in the event a tethered balloon (if selected) becomes untethered, it must have a rapid deflation device capable of bringing the craft back to the surface by releasing the lifting gas. This device must be automatic, meaning that it operates independently of any user input. The sections below will cover the most reasonable rapid deflation devices. These are an active pressure release system in the form of an electronic solenoid valve, a passive pressure release system in the form of a safety relief valve, and some sort of device that pops the balloon, such as a needle or another pointed object. All options are explored in detail in Appendix section 10.2

3.1.11. Ground Processor

To facilitate the user commands with the airborne vehicle and receive/store the data output from the instrument suite, a ground processor will be necessary. The ground processor may also be responsible for the post-processing of the sensor data recovered from the instrument suite. The possibilities for ground processor are explored in Appendix 10.2

3.2. Trade Study Process and Results

3.2.1. Flight Vehicle

The flight vehicle will be one of the most critical components of the design. This component will serve to elevate and sustain the altitude of the sensor suite, including the IR camera. The flight vehicles traded are weather balloon, aerostat, and UAV multirotor. Due to FAA requirements sections 104 and 107, any UAV including a tethered multirotor would require a pilot on site at all times. This need for a pilot would violate the customer requirement for an autonomous system.

Table 4: Description and Rationale of Flight Vehicle Criteria

Criteria	**Weight**	**Rationale**
Vehicle Cost	25 %	The flight vehicle is the most costly part of the flight vehicle trade study, and needs to be reasonably within the allocated budget.
Propellant Cost	10 %	The propellant cost can drive up the flight vehicle budget significantly, as multiple tests will need to be conducted. Cost to fly the vehicle per flight needs to be reasonably within the allocated budget.
Flight Endurance	25 %	The flight vehicle needs to be able to fly for multiple hours per flight, as this is dictated by the flight duration requirements.
Ease of Setup	10 %	The flight vehicle needs to be able to be set up in a reasonable amount of time.
Susceptibility to Weather	10 %	The flight vehicle needs to be able to fly and withstand light breezes and moderate windspeeds. If the flight vehicle has to be brought down every time there is moderate wind, the cost of operation rises significantly, and significant amounts of data is lost.
Camera Stability	5 %	The flight vehicle needs to be able to stabilize itself and the camera in the wind, as image data needs to be clear and consistent to be processed. This can range from simple camera shake (0.5Hz to 3Hz), to engine vibrations encountered when imaging from a moving vehicle or helicopter (10Hz to 20Hz).
Reusability	15 %	The flight vehicle needs to be reusable. The cost per flight will be significantly increased if the flight vehicle cannot be reused without servicing / replacing.

The flight vehicle is expected to take up a large portion of the budget. Thus, flight vehicle cost must be kept at a minimum. Due to the necessity for several test periods, each increasing in duration, multiple flights worth of propellant will be consumed throughout testing. Propellant cost should also be kept to a minimum to allow more testing as necessary. The largest flight endurance is decided to be one day with extrapolation to show possibility of one week. Because of this length, flight endurance should be as high as possible. Although not a major factor, the ease of set up should be conducive for only the occupants of the delivery pickup truck to complete setup in an afternoon. The entire system is not meant to operate on adverse weather conditions. However, each system was weighted based on its ability to withstand various windspeeds. Due to the cost per flight, the higher the number of flights for a single vehicle before servicing or replacement, the better.

Table 5: Description of Metric Used

Criteria	1	2	3	4	5
Cost of Vehicle	>$3000	$2000-$3000	$1000-$2000	$500-$1000	<$500
Cost of Propellant (Per flight)	>$100	$50-$100	$25-$50	$10-$25	<$10
Flight Endurance	<1 hour	1-3 hours	3-5 hours	5-8 hours	>8 hours
Ease of Setup	>3 hours	2-3 hours	1-2 hours	30mins-1 hour	<30 mins
Susceptibility to Weather (Withstand windspeeds)	<10 mph	10-25 mph	25-50 mph	50-75 mph	>100 mph
Camera Stability (Withstands shake)	0.5 Hz - 1 Hz	1-5 Hz	5-10 Hz	10-20 Hz	>20 Hz
Reusability	1 time use	2-5 uses	5-20 uses	20-50 uses	>50 uses

Table 6 is the summary of the flight vehicle trade study. Although a weather balloon poses issues with leakage and reusability, it has scored the highest and is allowable per FAA regulations.

Table 6: Flight Vehicle Trade Study Matrix

Flight Vehicle Criteria	Weather Balloon	Aerostat Balloon	UAV Multirotor
Cost of Vehicle	5	1	2
Cost of Propellant (Per flight)	3	3	5
Flight Endurance	4	5	2
Ease of Setup (by 1 person)	3	4	5
Susceptability to Weather (Withstand windspeeds)	2	4	1
Camera Stability (Withstands shake)	4	4	5
Reusability	2	4	4
Weighted Totals	**3.55**	3.40	2.95

3.2.2. Camera

The camera will affect payload weight, dictate the height of the structure, the quality of the images, and alter power requirements. The quality of the images will depend on the operational wavelength band of the camera. It was deduced that Landsat wavelengths for soil moisture detection lie within a 0.85-2.3 μm band-gap. The coverage area will be decided by FOV and resolution of the camera. As the height increases, a smaller FOV is required for a fixed resolution. The power draw will depend on the sensor array of the camera and internal processing speed.

The biggest limiting factor for the team was the cost of the camera. For the wavelengths of interest, prices range anywhere from $1,000 to $70,000. To ensure the budget is not completely consumed by the camera, the cost is weighed at 25%. Similarly, the data will not be useful to the customer if the right wavelengths are not used. Thus, the wavelength criteria is weighted by 25%. A higher camera resolution will increase pixel density per area at a constant height and allows us to gather images of larger coverage area. The larger the coverage area, the more cost efficient the overall system becomes per flight. For this reason the resolution criteria is weighted at 12.5%. Another constraint on the area to be imaged is the FOV of the camera lens. For a constant height, the coverage area increases with FOV, until a a coverage area equal to the pixel coverage area is reached. Past this point, images will not meet the pixel requirement. The dependence on resolution for FOV is the reason it is weighted at 10% rather than 12.5%. Note that the FOV is related to the focal length of the camera and is used interchangeably.

Table 7: Camera Criteria Definition

Criteria	**Weight**	**Rationale**
Cost of Camera	25%	Baseline budget is $5,000 for the project. From the research, IR cameras in the appropriate wavelengths are expensive ($1,000-$70,000). This means that a camera will allot to 20% of the budget at minimum. Because of its significance, camera cost was given a weight of 25%.
Wavelength Range	25%	Without the proper wavelengths, the images will not be useful to the customer. Therefore, the wavelengths captured by the camera have been given a weight of 25%.
Resolution	12.5%	Higher resolution will allow us to take images with higher coverage area. This allows for a higher margin of error for imaging. For these reasons, resolution has been given a weight of 12.5%.
Focal length	10%	A larger field of view will allow for a larger coverage area. Coverage area is important in keeping the camera lower to the ground but is bound by the pixel requirement. These factors result in a weight of 10% for focal length.
Ease of integration	10%	Communicating with the camera for full autonomy will be a crucial part of the design, so the less software that needs to be developed, the better. Modern IR cameras usually have software that provides a simple interface for prescribing commands. Therefore, integration has been given a weight of 10%.
Resilience	7.5%	To operate outside, the camera should be resilient towards shock, vibrations, and a wide range of temperatures. Most testing will take place in Colorado, USA, where the growing season temperature ranges from 85^{o}F to 23^{o}F meaning that resilience has been given a weight of 7.5%.
Power Draw	5%	Power draw will determine the size and complexity of power unit, but cameras tend to require low amounts of power, therefore, power draw has been given a weight of 5%.
Weight	5%	The camera will be on the instrument suite and will need to be suspended. For this reason its mass is included in the study although cameras tend to not be too heavy, meaning that it has been given a weight of 5%.

For the sake of autonomy, the camera must be able to take images at some prescribed cadence. This can be done easily with the right software and knowledge of the appropriate computing languages. For this reason, ease of integration is another part of the trade space and was weighed by 10%. This weight was chosen because most commercial IR cameras have existing software associated with them. The system could be exposed to the elements- rain, hail, snow- so the camera must be able to operate within a wide range of temperatures and conditions. The resilience of the camera was also an import spec to trade and was weighed at 7.5%. Power and weight will put strain on the batteries and structure respectively, and were considered in the trade study. Although important, cameras typically do not require large amounts of power, nor do they weigh much. Both power and weight were weighed at 5%.

Table 8: Camera Criteria Levels

Criteria	**1**	**2**	**3**	**4**	**5**
Cost of camera	price > $10,000	$10,000 > price > $7,500	$7,500 > price > $5,000	$5,000 > price > $2,500	price < $2,500
Wavelength	covers none of the Landsat wave length bands	covers 1 of the Landsat wavelength bands	covers 2 of the Landsat wavelength bands	covers all 3 of the Landsat wavelength bands	covers all of the Landsat wavelength bands and can change filters
Resolution	65,536 Pix <= res	81920 > res > 65,536	327,680 > res > 81920	1.9 Mpix > res > 327,680	res > 1.9Mpix
Focal Length	less than 10 mm or greater than 60 mm	between 10 mm and and 60 mm	between 20 mm and 55 mm	between 35 mm and 50 mm	variable focal length
Ease of integration	no existing software and can't be controlled digitally	no existing software	existing software	existing software can interfaced with known language	existing software has GUI and can interface with known language
Resilience	operating temperature range not within for growing season temp range	some operating temps lie in growing season temp range	operating temps lie in the growing season temp range	operates in growing temp ranges and has been tested for thermal, vibrational shock, and humidity	protected from extreme weather conditions
Power Draw	Power >= 60 W	60 W > Power >= 40 W	40 W > Power >= 24W	24W > Power >= 12W	12W > Power
Weight	mass >= 11 lbs	11 lbs > mass >= 4.5 lbs	4.5 lbs > mass >= 2.25 lbs	2.25 lbs > mass >= 1.1 lbs	mass < 1.1 lbs

To score each camera, the team developed a 1-5 scale for each criteria. The cost criteria was scored on fractions of the baseline budget (2, 1.5, 1, and $\frac{1}{2}$), as seen in Table 8. $10,000 is double the baseline budget and would be difficult to find enough money to finance. The wavelength scores depended on their prominence in the Landsat wavelengths. For example, an IR camera capable of imaging between 0.3 - 0.9 μm would score a 2, at it only contains one of the appropriate Landsat bands. Resolution and focal length are scored on their coverage capabilities. Although a larger FOV provides a wider coverage, the images will begin to incorporate undesirable features such as the ground station and tether system. For this reason the FOV is bounded at a maximum (10 mm) and a minimum (60 mm). Ease of integration was scored on all possible scenarios: (1) there is no possible way of controlling the cadence of image capturing (5) full control of the imaging system with low amount of work required. A similar approach was taken for determining the resilience scale. Extremes for resilience : (1) the camera could not operate in any of the appropriate temperatures and (5) the camera operates in all appropriate temperatures and can withstand extreme environmental conditions. The scale for power drawn was based off the wattage provided by a single car battery, largest electrical storage device traded on. The weight scale was designed after all the cameras found through out the study. This is because camera weights may very but never reach weights that exceed 10 lbs. So for a camera heavier that 10 lbs a score of (1) was given. The weight of 10 lbs was cut roughly in half to 4.5 lbs and given a score of (2) this was done again until a score of (5) was reached. Please refer to Table 8 for graphical representation of the scales.

From the above criteria and the selection presented in Table 4.2, a trade study matrix was made and can be seen in Table 9 below. For values that could not be found, a score of the three was given. This is because the camera should not be assumed to have a high or low performance, but a mid-range one.

Table 9: Camera Scores

Criteria	**ZEPHIR 2.5**	**FLIR Duo Pro R**	**EO-2223 NIR**	**Micro-SWIR 640CSX SWaP Optimized Camera**
Cost	1	3	5	1
Wavelength	5	1	3	4
Resolution	2	3	5	3
Focal length	3	2	3	3
Ease of integration	4	4	3	3
Resilience	3	2	3	3
Power draw	1	3	5	3
Weight	2	3	5	5
Weighted Totals	2.75	2.6	**3.78**	3.03

3.2.3. Power Source

In order for the flight vehicle and ground station to operate properly, a power source capable of supplying enough power for the entire duration of the testing periods is needed. For the power source trade study, the team considered various batteries with different chemical compounds, as well as renewable sources such as solar. Each power source trade will be ranked by the cost of the power source, integratability, safety, ease of setup, durability and the lifetime. The expected power draw is 0.7 Amps. Ideally, the battery will have double the battery capacity required for the testing period stored in the power supply to account for any additional power losses not yet predicted.

Table 10: Power Source Criteria Definition

Criteria	Weight	Rationale
Cost	20%	While the power supply is critical to operations, the budget is very limited so the cost of the power source is of significance.
Integratability	20%	The more soldering and wires required to setup the power supply the more losses will be experienced. Additional difficulties associated with stepping up or down the voltage supplied.
Safety	10%	Battery safety is similar for all battery types, however some batteries are more likely to be dangerous than others. Since a large capacity power supply operating on 12 V is needed, the risks associated with different power supply options should be considered.
Ease of Setup	10%	Once the battery system is fully integrated safely, the set up should just consist of plugging power supply into the ground station. Therefore ease of setup really depends on weight of the power supply and possible setting up solar panels.
Durability	20%	How much is the power source effected by temperature changes and extended continuous operation.
Lifetime	20%	This system is intended to be used over and over again by farmers. The more time the system can be used without needing to preform power source maintenance the better.

The cost of the power source is important because a very limited budget is constraining. Since an analysis must show that there is enough power to operate for up to a week, the power source needs roughly 230Ah. This much capacity is not cheap for certain batteries, which is why the cost is weighted with 20%. The integratability of the power source is an important factor because of the limited time available to build and test the system. There are other important components and challenges in this project, so the less time needed to use building a power supply to integrate with the rest of the project the better. The weight of integratability is weighted with 20% as well. The difficulty of integrating the power source will stem from how many different components are required for it to function. These components may include batteries, solar panels, and charging controllers. The safety weighting was selected at 10% because most batteries have the same safety issues associated with them. Regardless of the battery type chosen, a charge regulator is needed to ensure that the battery is not overcharged, which can lead to safety hazards. It is also necessary to ensure the batteries are charged in a safe enclosure to protect the batteries from the weather. Some batteries are inherently more susceptible to be safety hazards if they are not charged and discharged with care. Lithium polymers and lithium ion batteries, for example, must be charged and discharged at specific rates, and cannot be charged when hot otherwise there is a risk of the batteries catching fire. The ease of setup is important to the trade study of the power supply because there is a set deployment and recovery time levied on the system. Thus, the ease of setup with 10%. The durability of the power supply is weighted at 20% as well because it is as important as the cost, lifetime, and integratability. Since power must be supplied outside in possibly inclement weather, the power source needs to be able to withstand non ideal conditions. No matter the power solution chosen, some sort of weatherproofing is necessary for the power source. Batteries will operate best in a dry, room temperature location, but they usually have a range of temperatures in which they can charge/discharge without becoming damaged. Battery power will drain faster in cold environments and can swell up in hot environments, so the durability scores were decided based off the safe operational temperature range of each battery type. The lifetime of the power source is an important weighting because the team aims to design this system to be reused many times. The life cycle of the power source is primarily dependent on the number of full charge/discharge cycles that a given battery compound can undergo, except in the case of solar, in which the lifetime is dependent on the lifetime of the panel and lifetime of the battery undergoing partial charge cycles.

Table 11: Power Source Criteria Levels

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$1200	$1200-$900	$900-$600	$600-$300	<$300
Ease of Integration	>12 components	12-9 components	9-6 components	6-3 components	<3 components
Safety	Power source requires careful management of charge/discharge cycles	N/A	N/A	N/A	Must practice normal battery safety to use power source. This includes issues with overcharging
Ease of setup (by 1 person)	>2 hours	1.5-2 hours	1-1.5 hours	0.5-1 hour	<30 minutes
Durability	<54°F ΔT	54-72°F ΔT	72-90°F ΔT	90-108°F ΔT	>108°F ΔT
Lifetime	<6 months	0.5-1 year	1-1.5 years	1.5-2 years	>2 years

Table 12: Power Source Scores

Criteria	**Car Battery**	**Solar panels w/car battery**	**Lipo batteries**	**Lithium Ion Batteries**	**NiMH Batteries**
Cost of Power Supply	4	4	1	1	1
Ease of Integration	5	5	1	1	1
Safety	5	5	1	1	1
Ease of Setup	5	4	5	5	5
Durability	5	5	3	3	3
Lifetime	1	5	5	5	4
Weighted Totals	3.60	**4.70**	2.60	2.60	2.40

3.2.4. Communications

Due to the current unknown data volume, each communication method was evaluated with the pursuit of finding a method that can provide data rates greater than 1.5 Mbps. This basis was arrived at by assuming a worst case science packet size of 800 Mbits and a transmission time of no longer than 10 minutes. With this basis in mind, each communication method was examined for implementation between an aerial vehicle and ground station. Table 13 presents the criteria traded against, their respective weightings, and justification for their selection. The greatest priorities are data rate, cost of components, and ease of integration. Criteria levels are defined in Table 14 with the final results of the trade presented in Table 15. Sources for each communication method can be found in the Appendix.

Table 13: Communication Method Criteria Definitions

Criteria	**Weight**	**Rationale**
Data Rate	30%	The goal of the project is to provide high resolution images at a high cadence. These images need to be transferred in a timely manner to reduce storage requirements and allow for quick processing. If data is not transmitted quickly it could result in the overwriting of science data. With this in mind, data rate was assigned a weight of 30%.
Cost of Components	25%	Cost is the constraining aspect of the project. The majority of budget will be dedicated to the science instrument and flight vehicle. As such, it is important to conserve budget wherever possible. These factors result in a weight of 25%.
Ease of Integration	25%	A communications system can be quite complex in its implementation. However, because the team does not have a large skill-set in communication hardware or methodology, the complexity of any system will be heightened. To overcome this the team is seeking to keep the system as simple as possible, resulting in a weight of 25%.
Power Draw	20%	Reducing power consumption reduces overall project cost and complexity. The communication system is not expected to be a large power draw resulting in a weight of 20%.

Table 14: Communication Method Criteria Levels

Criteria	**1**	**2**	**3**	**4**	**5**
Data Rate	<1.5 Mbps	1.5 Mbps - 24.9 Mbps	25 Mpbs - 49.9 Mbps	50 Mbps - 75 Mbps	>75 Mbps
Cost of Components	>$100	$80-$99	$60-$79	$40-$59	<$40
Ease of Integration	Complex beyond reason	Extensive time required to implement and develop	Some time and complex techniques required to get working	Minimal time required to develop and implement	Nearly no effort required
Power Draw	>2.5 W	2.49 W - 2 W	1.99 W - 1.5 W	1.49 W - 1 W	<1 W

Table 15: Communication Method Scores

Criteria	Serial Peripheral Interface	Ethernet Local Access Network	Radio Communication (2.4 GHz)	Wireless Local Access Network	RS-485
Data Rate	5	5	1	5	3
Cost of Components	4	5	1	1	5
Ease of Integration	1	3	5	5	2
Power Draw	3	3	3	2	4
Weighted Totals	3.35	**4.10**	2.4	3.40	3.15

As seen in Table 15 the Ethernet LAN (LAN) and Wireless Local Access Network (WLAN) are ahead of other candidates. These two systems present a similar solution, however one is via a wired connection and one is wireless. Based upon the trade study the LAN solution is the best for this project based on the low cost of components and smaller power draw.

3.2.5. Microcontroller

As discussed earlier, an on-board microcontroller is necessary to control the instrument suite electronics and transfer data to the ground station. Table 16 shows the definitions of the criteria used to study the trade space of the microcontroller.

Table 16: Microcontroller Criteria Definition

Criteria	Weight	Rationale
Processing Power	35%	The primary purpose of the microcontroller is to process images and data downlinked from the flight vehicle, and run all autonomous functions. As such, the processing power determines the speed and volume of deliverable data, and the overall functionality of the mission.
Software Integration	35%	The autonomous nature and scope of this mission requires an easy to use language that is well known by the software team.
Hardware Integration	15%	This project shall use multiple sensors, which must be connected to the microcontroller. As such, the number and type of input/output interfaces will determine the ease of which this group can interact with the microcontroller.
Power Draw	10%	Given the duration of the mission, the power consumption of the microcontroller is an important consideration. The existence of a ground station also allows for a large power reservoir, reducing the significance of this category.
Cost	5%	This project's budget is predicted to be tight, however, microcontrollers are relatively inexpensive.

Table 17: Microcontroller Criteria Levels

Criteria	**1**	**2**	**3**	**4**	**5**
Cost	>$80	60–80	$50-60	$40-50	$0-40
Power Draw	>5 W	4-5W	2-4W	1-2W	0-1W
Processing Power	Average SRAM and Flash Memory of less than 256 KB	Average SRAM and Flash Memory of less than 512 KB and more than 256 KB	Average SRAM and Flash Memory of less than 1024 KB and more than 512 KB	Average SRAM and Flash Memory of less than 2048 KB and more than 1024 KB	Average SRAM and Flash Memory of more than 2048 KB
Software Integration	Low level language that must be learned	Low level language that requires some learning	High level language that must be learned OR Known low level language	High level language that requires some learning	High level language that doesn't need to be learned
Hardware Integration	Requires intermediate component to interface with board	Has less than 10 IO pins	Has sufficient IO pin count	Has sufficient IO pins and a data port (eg USB)	Has an excess of IO pins and 2 or more data port types

Table 18: Microcontroller Scores

Criteria	**Raspberry Pi 4 Model A+**	**Arduino Mega**	**BeagleBone Black**	**Silicon Labs Pearl Gecko**
Cost	2	5	3	1
Power Draw	1	4	3	5
Processing Power	5	2	4	3
Software Integration	5	4	2	3
Hardware Integration	5	3	4	3
Weighted Total	**4.45**	3.2	3.15	3.10

As clearly shown in 18, the Raspberry Pi would be the best microcontroller candidate for the needs of this project due to its impressive processing power and ease of software and hardware integration.

3.2.6. Data Calibration Method

While the group determined that interpreting the NIR images gathered as usable soil moisture data was outside the scope of this project, some soil moisture measurements of the observed field will be taken for future data calibration and provided to the customer. Table 19 shows the criteria, their respective weights, and justifications. Table 20 defines the values for each of the criteria at the five possible levels. For Table 20, %VWC stands for volumetric water content. The resulting trade study is displayed in Table 21 with all sources for calibration methods presented in the Appendix.

Table 19: Data Calibration Criteria Definitions

Criteria	Weight	Rationale
Accuracy	30%	Calibration data is being provided to ensure that the infrared data provided can be accurately translated to soil moisture. Only with accurate calibration data can the deliverable data be certainly useful. As such, the accuracy of the calibration data is given 30% weighting.
Cost of Components	10%	Cost is the limiting factor of the entire project. Other aspects of the project (such as camera) are more critical for success, and as such will be where the majority of the budget goes. Minimizing costs in as many areas as possible helps ensure every system is properly funded. As such cost has been given 30% weighting.
Entire Field Covered	10%	Being able to collect data over the entire field is important as the calibration data is a more accurate representation of the data gathered by the project. It is of equal importance to temporal and spatial resolution, therefore it is weighted at 10%.
Spatial Resolution	10%	Spatial resolution denotes the calibration data's ability to represent the discrete locations of data provided by the project's camera (49 in^2 per pixel). As the pixel-to-ground ratio is a driving requirement, having calibration data with a similar spatial fidelity helps to resolve inaccuracies with a higher level of detail. Its importance results in a weight of 10%.
Temporal Resolution	30%	Temporal resolution denotes the method's ability to gather data repeatedly. As the project's goal is to gather data of a fixed location for an extended period of time, calibration data over a similar time frame ensures accuracy, resulting in a weight of 10%.
Ease of Integration	5%	The difficulty of integrating any system must be taken into account as it will take the team away from working on other aspects of the project. With this in mind, it is given a weight of 5%.
Intrusiveness	5%	One of the project's driving requirements is to be non-intrusive. While the data calibration probes are not expected to be non-intrusive, it is still beneficial, resulting in a weight of 5%.

Table 20: Data Calibration Criteria Levels

Criteria	1	2	3	4	5
Accuracy	>5% VWC	4%-4.9% VWC	3%-3.9% VWC	2%-2.9% VWC	<2% VWC
Cost of Components	>$60 per probe	$46-$60	$45-$30	$29-$6	<$6 per probe
Entire Field Covered	The entire field does not have representative calibration data.	N/A	N/A	N/A	The entire field has representative calibration data.
Spatial Resolution	Capable of providing data 10x or larger than the size of a science pixel.	5x-7.5x size of science pixel	2.5x-4.9x size of science pixel	2.49x - 1.1x size of science pixel	Provides data on the same scale or smaller than that recorded for science
Temporal Resolution	Capable of providing calibration data only once.	N/A	Capable of providing calibration data multiple times but not at the cadence of imaging.	N/A	Capable of providing calibration data at the same cadence as images are captured.
Ease of Integration	Complex beyond reason	Extensive time required to implement and deploy.	Some time and complex techniques required to get working.	Minimal time required to deploy and get working.	No effort required.
Intrusiveness	>0.75 inch hole	0.5 in - 0.74 in hole	0.49 in - 0.25 in hole	0.1 in - 0.24 in hole	Not intrusive

Table 21: Data Calibration Scores

Criteria	SparkFun Soil Moisture Sensor	UAS Drone (Black Swift S2)	Vernier Soil Moisture	Vegetronix In-Situ
Cost	5	5	1	4
Intrusiveness	4	5	2	3
Accuracy	3	3	2	4
Ease of Integration	4	5	3	3
Entire Field Covered	1	5	1	1
Temporal Resolution	5	1	5	5
Spatial Resolution	5	3	5	5
Weighted Totals	3.9	**3**	3.05	3.6

The trade study in Table 21 shows the SparkFun Soil Moisture Sensor option to be the best. It is an affordable, relatively simple choice and will allow data to be collected through time unlike the UAS, which can only collect data once. In addition to using SparkFun Soil Moisture sensors, the ”baked dirt” method will be employed to get accurate moisture levels. This method can also be used to calibrate the soil moisture data captured by the sensors.

3.3. Design Requirements Flow Down

The functional requirements listed in Table 3 were written to provide direction in choosing a baseline design that could meet mission objectives. These are major requirements that define all others and are provided with their rationale and sources. Design requirements (DRs) were then created based on functional requirements to give further detail on how functional requirements should be met. There are two levels of design requirements used in this project. The higher level are deemed parent DRs and low level requirements that flow from parent DRs are called child DRs.

Parent DRs are considered major requirements, as they break functional requirements into more manageable segments. The following matrix contains all of the requirements for the project. All requirements are listed with their motivation, as well as responsible subsystems and verification methods. Further detail on verification is present in section 5. The baseline design section follows; all choices made for the baseline design were chosen to meet design requirements.

ID - L1	ID - L2	ID - L3	Requirement	Motivation	Verification Method	Subsystem applicability
FR1			**The flight vehicle shall be deployable from the ground to an altitude between 100 - 150 ft.**	**The flight vehicle must carry the instrument suite to an altitude capable of imaging a large area of soil but must not surpass 150 ft altitude due to FAA regulation. Source: FAA and mission success criteria**		**Ground Structures Flight Vehicle Airborne Structures Imaging system Software Communications Power Electronics Safety and Test**
	DR1.1		The system shall fit in a 5'x5'x2' pick-up truck bed.	The system must be easily transportable in a pickup truck.	Test: the system fits in a truck bed.	Safety and Test Ground Structures Flight Vehicle Airborne structures Power
	DR1.2		The system shall be set up and deployed in no more than 24 man-hours.	As mandated by the customer, the system must be deployable in a specific amount of time.	Test: Setup and deployment is performed in no more than 24 man-hours.	Ground Structures Flight Vehicle Airborne Structures Imaging system Software Communications Power Electronics
		DR1.2.1	The system shall be capable of being separated into carriable components with each component weighing less than 55 lbs.	To ensure deployment can be completed by individuals without additional equipment, individual components must be within this OSHA specified weight limit.	Inspection: Weigh each individual component and ensure each is within the limit.	Safety and Test Ground Structures Flight Vehicle Airborne Structures Power
		DR1.2.2	The flight vehicle shall be launched to an altitude between 100 - 150 feet from the ground.	For a basic camera, this altitude range is required to obtain a field of view that meets the pixel requirement.	Inspection: After deployment, observe altitude of the payload by triangulating tether length and angle.	Ground Structures
	DR1.3		The flight vehicle shall maintain an altitude between 100 - 150 feet for flight duration.	In order for images to be taken at a consistent altitude, the flight vehicle must maintain that altitude	Test: During final flight, verify balloon does not dip below 100 ft with onboard sensors.	Flight vehicle
		DR1.3.1	The flight vehicle shall maintain a constant altitude in the acceptible range plus or minus 10 feet.	Large variations in altitude affect image quality.	Test: Altitude data over a day-long flight will be observed or backed out through post-processing and verified to be within the acceptible range.	Flight vehicle
	DR. 1.4		The flight vehicle shall be secured to the ground structure.	The system needs to stay in one general place.	Inspection: The flight vehicle is successfully tethered to the ground and does not break free.	Ground Structures Airborne Structures
		DR 1.4.1	The tethering structural elements shall each have their own factor of safety of 3 for failure under inclement conditions.	To ensure the vehicle maintains its position, support structures must keep the vehicle in place without fear of failure.	Test: The tethering elements shall each withstand a load 1.3 times their yield load.	Ground Structures
FR2			**The flight vehicle shall be capable of operating in the air for 1 day.**	**The system must operate and collect images for a day, with at least 80% of the flight being uptime. Source: Required by customer**		**Flight Vehicle**
	DR2.1		The flight vehicle shall be provided enough propellant to withstand a day long flight.	Lifting gas must be able to sustain a one day flight of the balloon to meet customer requirements.	Test: The flight vehicle will be flown for a day.	Flight vehicle
		DR2.1.1	The flight vehicle shall have enough propellant to stay at an altitude between 100 - 150 feet for a day long flight.	Flight vehicle must remain at similar altitude for images to be aligned properly.	Test: The flight vehicle will be flown for a day within the altitude range.	Flight Vehicle

ID - L1	ID - L2	ID - L3	Requirement	Motivation	Verification Method	Subsystem applicability
FR3			**The system shall be provided enough power to sustain a 1 day flight.**	**The system must receive continuous power to remain power positive and collecting images. Source: FR2 and mission success criteria**		**Power**
	DR3.1		The system shall not draw more power than the battery can provide.	Power supply is designed to provide minimum of 12 V at 115Ah, thus can provide at least 69 watts of power over one hour.	Test: Power measurements verify the system is drawing less than 69 watts of power.	Power
FR4			**The imaging system shall be able to autonomously image with a resolution of 7x7 square inch per pixel for 80% of 1 day.**	**An autonomous system allows for limited occurance of human error. This resolution will provide higher fidelity data than any current solution for detecting soil moisture. Source: Required by customer**		**Imaging system software**
	DR4.1		The imaging system shall produce infrared images within the wavelengths of 0.9 to 1.7 micrometers.	This wavelength range holds the absorption bands of both soil and water.	Inspection: The imaging system's specs claim to take take images in this range.	Imaging system
	DR4.2		The imaging system shall produce images of the ground with dimensions of 300 square feet.	With a basic camera and the pixel requirement at the minimum altitude specified above, the area coverage is 300 square feet.	Inspection: Reference points are a known distance apart so ground coverage area can be determined in an image in post-processing based off of length ratio in image to actual between references.	Imaging system
		DR4.2.1	The imaging system shall produce images with a resolution of 7x7 square inch per pixel at flight altitude.	Customer provided pixel requirement.	Test: Knowing camera specs, flight altitude, and determined testing area, the pixel requirement can be backed out.	Imaging system
	DR4.3		The imaging system shall capture images during operational conditions.	Allows greatest chance of attaining useful data.	Test: images are taken in edge cases of operational conditions and work.	Imaging system software
		DR4.3.1	The camera shall operate within temperatures from 10 to 70 degrees Fahrenheit.	The camera must be able to sustain minimum and maximum growing season temperatures.	Test: Test the camera for operational capability at minimum and maximum growing season temperatures.	Imaging system
	DR4.4		The imaging system shall have the capability to image for 80% of any testing period during operational conditions.	Customer provided uptime requirement.	The imaging system runs for 80% of the testing period during operation conditions.	Imaging system
		DR4.4.1	The imaging system shall capture images autonomously.	Customer provided autonomy requirement.	Inspection: The imaging system captures images without user reliance.	software imaging system
		DR4.4.2	Imaging data shall be taken 15 minutes apart.	Customer provided cadence requirement.	The imaging system timestamps of images are compared over a test duration.	software imaging system
		DR4.4.3	The imaging system shall take 4-16 pictures in a burst during image collection.	Burst image collection allows for a higher quality image to be captured, desired by customer.	Inspection: The imaging system collects 4-16 pictures in a burst every image collection cycle.	imaging system software
FR5			**The instrument suite shall take and process environmental data for a day.**	**Environmental data must be provided to the customer to aid in soil moisture algorithm development and quality flagging images. Source: Required by customer and mission success criteria**		**Electronics communications software**
	DR5.1		The instrument suite shall observe and record environmental data for the duration of a one day flight.	Continuous environmental data must be taken to determine if weather conditions are operational.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
		DR5.1.1	The instrument suite shall record temperature every 10 seconds.	Environmental data must be collected often enough for changes in weather to be detected.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
		DR5.1.2	The instrument suite shall record humidity every 10 seconds.	Environmental data must be collected often enough for changes in weather tc	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
		DR5.1.3	The instrument suite shall record acceleration in all 3 axes of the instrument suite's inertial frame every 0.1 seconds.	Inertial measurements must be collected often enough for changes in flight vehicle orientation to be detected.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
		DR5.1.4	The instrument suite shall record gyroscopic information in all 3 axes of the instrument suite's inertial frame every 0.1 seconds.	Inertial measurements must be collected often enough for changes in flight vehicle orientation to be detected.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
		DR5.1.5	The instrument suite shall record windspeed every 10 seconds.	Environmental data must be collected often enough for changes in weather to be detected.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software

ID - L1	ID - L2	ID - L3	Requirement	Motivation	Verification Method	Subsystem applicability
		DR5.1.6	The instrument suite shall record GPS data every 10 seconds.	Environmental data must be collected often enough for changes in weather to be detected.	Test: Timestamps of downlinked environmental data will verify if data was collected.	Electronics software
	DR5.2		The instrument suite shall determine if the current environmental conditions allow operational conditions.	Images will only be aligned if operational conditions are present.	Inspection: Images are not aligned if flagged during non-operational conditions.	Software
		DR5.2.1	Data from the humidity sensor, temperature sensor, gyro, accelerometers, and wind speed sensors shall be used to determine if the current environmental conditions are operational.	Environmental sensors can be used to define operational conditions (high wind, temperature)	Test: When non-operational conditions are simulated, images are flagged for non-operational conditions.	Software
		DR5.2.2	If inclement weather conditions are persistently sensed in the minute leading up to image capture, the instrument suite shall flag the subsequent image for poor quality.	Images will only be taken if operational conditions are present.	Test: When non-operational conditions are simulated, images are flagged for non-operational conditions.	Software
FR6			**Data shall be transferable from the instrument suite to the ground station.**	**The ground station must first receive data from the instrument suite to store it for the duration of the test. Source: Required to satisfy project objectives**		**Software communications imaging systems**
	DR6.1		Data transfer shall be autonomous.	Customer provided autonomy requirement.	Test: Data transfer shall be performed without user reliance.	communications software
		DR6.1.1	The size of images shall be transmitted in metadata from the instrument suite.	Allows for filekeeping and packetizing information.	Test: Perform test on ground that compares to data size calculated by instrument suite.	imaging system software
	DR6.2		Data shall be stamped with the time of collection by the instrument suite before being sent to ground station.	Allows for post processing to go smoothly.	Test: Verify timestamps match time of data collection.	software
		DR6.2.1	Each image shall be stamped with time of capture.	Allows for post processing to go smoothly.	Test: Verify timestamps match time of data collection.	software
		DR6.2.2	Environmental data points transmitted to the ground shall be stamped with time of collection.	Allow for integration into customer post-processing.	Test: Verify timestamps match time of data collection.	software
FR7			**Data shall be stored by the ground station and post-processed.**	**Test data is a deliverable to the customer and must be stored and organized into a useful format prior to delivery. Source: Required by customer and critical for mission success**		**Software communications imaging systems**
	DR7.1		The ground station shall store data for the duration of the flight.	All data received should be exported for customer calibration purposes.	Test: Verify all expected environmental data and images are stored on the ground through post-processing.	software
		DR7.1.1	The process responsible for data storage shall run for one day.	Data storage must be performed for the duration of the flight to account for all collected data.	Test: Process runs without failing for a day.	software
		DR7.1.2	The ground station shall be able to store 100 GB of data.	6.38 GB required for 10MB/pic over 5380 pics for 10 picture burst per imaging block. This is significantly less than 100 GB so 100 GB provides upscalability.	Test: Verify by inspection of storage specifications.	communications software
		DR7.1.3	Software shall flag when an outlier or obstruction of reference points occurs in an image.	Obstructions cause poor image data and we do not want the customer to consider these.	Test: Take images with obstructions in view and verify they are recognized by software.	software
	DR7.2		Errors received from the instrument suite shall be detected and logged.	Possible errors should be caught and logged to make data processing and error diagnosis easier.	Test: Intentionally cause a data logging error on the instrument suite and verify an error is detected.	software
		DR7.2.1	The size of the image transmitted from the instrument suite in metadata shall be compared to the image data received by the ground station.	This verifies the full image is downlinked without corruption which is useful for post-processing.	Test: Send an image with its size in metadata and compare it to the size calculated on the ground.	software
		DR7.2.2	Any detected discrepancy between the data transmitted and received shall be logged.	Possible errors should be caught and logged to make data processing and error diagnosis easier.	Test: Induce missing data and check that it is logged on the ground.	software

ID - L1	ID - L2	ID - L3	Requirement	Motivation	Verification Method	Subsystem applicability
	DR7.3		Images shall be post-processed.	Customer required.	Test: Take a set of similar images and aligning them.	imaging system software
		DR7.3.1	Images shall be aligned in post-processing.	Customer requested aligned images for their calibration purposes.	Test: Take a set of similar images and aligning them.	imaging system software
		DR7.3.2	Images shall be aligned in post-processing.	Customer requested aligned images for their calibration purposes.	Test: Take a set of similar images and aligning them.	imaging system software
		DR7.3.3	Reference points on the ground shall be used for image alignment.	Reference points give keypoints for image alignment algorithm.	Inspection: At least three near-IR markers on the ground are visible by the camera on the instrument suite.	imaging system
	DR7.4		In post-processing, the software shall packetize environmental data into files that contain 15 minutes of observation.	Makes calibration and data visualization easier to section by image collection cycle.	Inspection: Verify packets contain 15 minutes of data.	software
		DR7.4.1	Environmental data shall be packetized into a uniform, human readable file format (e.g. netCDF, h5, CSV, etc.)	Data processing and visualization is simpler when uniformly formatted and human readable.	Inspection: Environmental data files are correctly processed into an acceptible format.	software
		DR7.4.2	Files shall begin within ten seconds of a scheduled image capture and end within ten seconds after the next scheduled image capture.	Data can be grouped with the image it coincides with.	Inspection: Compare earliest times in packet with image collection times.	software
		DR7.4.3	Environmental data packets shall be stamped with the time of the first data entry.	This dictates a uniform logging system.	Inspection: Verify time stamps on packets match the time of the first data entry.	software
	DR7.5		All data downlinked from the instrument suite shall be stored on the ground station processor.	Customer wants all collected useful data.	Inspection: Verify the amount of data expected for a day long flight is stored by the ground station processor.	communications software
		DR7.5.1	Raw image data shall be titled by time and date.	Allows for easier data post-processing.	Inspection: Verify that image data is stamped with time and date.	software
		DR7.5.2	Raw image data shall be accessible to the user via the ground station's file system.	Customer required data to be easily accessible by user.	Inspection: Verify that raw image data is accessible by user on the ground.	software
FR8			**The flight vehicle shall be retractable to the ground from an altitude between 100 and 150 ft.**	**The system (except the flight vehicle) must be reusable and must therefore be collectable at the end of the test period. Source: Required by customer and critical for mission success**		**ground structures**
	DR8.1		The system shall be retracted, broken down, and stowed in no more than 24 man-hours.	As mandated by the customer, the system must be retractable in a specific amount of time.	Test: Tear-down is performed in no more than 24 man-hours.	ground structures
		DR8.1.1	The flight vehicle shall be retracted from the specified altitude to the ground without damaging the instrument suite.	The instrument suite holds valuable and expensive equiment that would be detrimental to the team if damaged.	Test: The flight vehicle is retracted and the instrument suite is still functional.	ground structures
FR9			**Soil moisture calibration data and GPS data shall be collected.**	**Baseline data must be collected for the customer to compare IR information to. This is required in order for ASTRA to develop a soil moisture model with accurate location information. Source: Required by customer**		**calibration electronics**
	DR9.1		Soil moisture data shall be collected by existing technology once per flight.	Customer required for soil moisture algorithm calibration.	Inspection: Soil moisture data is collected using existing technology.	calibration
	DR9.2		Soil moisture data shall be collected over the testing area of 300 square feet.	Customer required for soil moisture algorithm calibration.	Inspection: Soil moisture data is collected over the entire testing field.	calibration
	DR9.3		GPS data shall be collected for the testing field.	Customer required.	Inspection: GPS data for the center of the testing field is collected.	electronics

ID - L1	ID - L2	ID - L3	Requirement	Motivation	Verification Method	Subsystem applicability
FR10			**The system shall comply with all ITAR requirements**	**The project must comply with ITAR requirements to be deployed and used. Source: Course driven, law driven**		**safety and test**
	DR10.1		The system shall not violate any specification restricted by ITAR.	Violating ITAR results in a heavy fine and legal action.	Inspection: All camera specs will be checked against ITAR regulations to make sure none are violated.	safety and test
FR11			**The flight vehicle shall comply with all FAA requirements**	**The project must comply with FAA requirements to be deployed and used. Source: Course driven, law driven**		**safety and test**
	DR11.1		The flight vehicle shall not be operated in any way that may cause harm to any persons or property.	Must not injure any teammembers, bystanders, or property.	Procedures shall be written and followed for all actions involving the flight vehicle (i.e. setup, teardown, etc.).	safety and test
		DR11.1.1	No objects shall be dropped from the flight vehicle if such action creates a hazard to any persons or property.	Anything dropped from the flight vehicle may cause significant harm to persons or property.	Inspection: All objects on the flight vehicle will be affixed, and emergency procedures in place in the event that they come detached.	safety and test
		DR11.1.2	The flight vehicle shall have a rapid deflation device onboard in the event of an emergency.	The flight vehicle must return to the surface quicky and safely in case of emergency.	Test: A rapid deflation device will be designed and integrated onto the flight vehicle.	safety and test
		DR11.1.3	If control of the flight vehicle is lost, the operator shall contact the nearest FAA ATC facility with the location, time of escape, and estimated path of the flight vehicle.	The FAA needs to keep track of the escaped vehicle, and we must retrieve it.	The nearest FFA ATC facility contact info will be readily available in the event that control of the flight vehicle is lost.	safety and test
	DR11.2		No person shall operate the flight vehicle without proper FAA and/or municipal permissions.	Must not trespass or operate illegally in any location.	All appropriate permissions will be acquired prior to the testing date.	safety and test
		DR11.2.1	The flight vehicle shall not be operated in a prohibited or restricted area without the permission of the controlling agency.	Must not trespass.	Operation of the flight vehicle will only occur over an area of which the proper permissions have been acquired.	safety and test
		DR11.2.2	The flight vehicle shall not be operated within five miles of the boundary of any airport.	It is unsafe to both the operator and airline passengers to operate near an airport.	Inspection:The testing area will not be within five miles of the nearest airport.	safety and test
	DR11.3		The flight vehicle shall be operated under all FAA safety regulations.	Must not injure any persons or property.	All flight procedures will comply to FAA safety regulations.	safety and test
		DR11.3.1	The flight vehicle shall be lighted when operating between sunset and sunrise.	Any other aircraft must be able to see the flight vehicle throughout the night.	Lights will be affixed to the balloon and its tethers and turned on between sunset and sunrise.	safety and test
		DR11.3.2	The flight vehicle shall not be operated from an area where the ground visibility is less than three miles.	Any other aircraft must be able to see the flight vehicle when visibility is low.	The flight vehicle shall not be operated under fog or other low visibility conditions.	safety and test
		DR11.3.3	The flight vehicle shall not be operated more than 500 feet above the surface of the earth.	Must not operate above FAA mandated limits.	The GPS data will verify that the flight altitude does not exceed 500 feet above the surface.	safety and test

3.4. Baseline Design

3.4.1. Flight Vehicle

After consideration of all the criteria, pros, and cons of each flight vehicle, the weather balloon was chosen as the flight vehicle for this project. The weather balloon is the least expensive option out of all the flight vehicles, which was the largest driving force for the choice. Weather balloons are the industry standard for scientific experiments, and the extensive documentation makes them simple to understand and use. However, there are two unknowns: First, the duration of flight for latex balloons at a static altitude is unknown as weather balloons are designed to fly up several kilometers and burst. Second, since they are designed to be a one time use application, the team does not have data on weather balloon reusability. Once again, the largest factor to the weather balloon being chosen is the availability and price of the balloons.

The second choice was the aerostat balloon, as it is perfect for the desired application, and has a history of use for long duration aerial photography and surveillance. It has the same cost of propellant for the weather balloon, is reusable, has a long flight endurance, has weather endurance, and can be easily set up. However, the cost of the aerostat and its ground structure is too expensive for the limited budget. UAV multirotors and airplanes are also simply too expensive. UAV multirotors are reusable and easy to set up, but do not have long duration capabilities and are very susceptible to changes in weather. Most importantly, any flight vehicle considered a UAV by the FAA, including tethered quadcopters, require a pilot on site during any flight. This requirement would not only be far too expensive, but violate the customer's requirement for autonomous data capturing.

3.4.2. Camera

The EO-2223 scored highest in the WIRMS trade study, Table 9. This is mostly due to its low cost compared to the other cameras and imaging wavelengths. The camera itself costs $1,400 and can image in 400 nm - 1000 nm wavelengths with an outstanding resolution (2.3 Megapixels), which will provide a larger maximum coverage area. Its spectral resolution includes one of the three relevant Landsat ranges[11](NIR). For these reasons, the EO-2223 was selected as the projects IR camera.

CAMERA LENS To widen the FOV of the camera along either axis, the camera will be equipped with a 16 mm C Series VIS-NIR Fixed Focal lens by Edmund optics. This lens cost roughly $520 and will be able to image 3600 ft^2 from a height of 118 ft.

CAMERA FILTER The selected camera's spectral range will fall mostly in the visible range as opposed to the NIR range. To ensure that the team can image in the NIR wavelengths, the camera will be equipped with the Edmund optics 700nm M25.5 x 0.5 Mounted Longpass Filter. This filter will allow the team to image in wavelengths from 700 nm - 2000 nm and costs $125.

Note: The customer, ASTRA, provided all pieces of camera hardware for this project.

3.4.3. Power Source

The solar panel with a lead acid battery was selected as the power source solution for this mission. Due to the longevity of the mission, batteries alone proved to be too costly. Using a lead acid car battery would provide three days of run time with out any charging before the battery became significantly drained. This means the power source can recover from a bad day of charging (cloudy, rainy, etc) with two good days of charging (6 hours of sunlight). The downside to using solar panels is the increase in difficulty of integrating the power supply and the difficulty of setup. The ease of setup will likely be a small difference compared to the other power source solutions. Integrating the solar panels with a lead acid battery will require a charging regulator to insure the batteries are not overcharged. This solution is more complex than simply connecting batteries in parallel/series, however the added benefit of generating power throughout the duration of the mission helped drastically with cost. These conclusions can be reinforced with the power source trade study table seen in Section 5 (Table 12).

SOLAR PANEL SELECTION The solar panel chosen for this project is a 300W monocrystalline solar panel. A 300W solar panel was chosen to ensure that the battery would not drain, even if testing during a cloudy day when insolation is low. Additionally, a high power rated solar panel was desired so that the system's power use can be extrapolated out to a week by analysis for the customer.

BATTERY SELECTION Initially, a standard lead-acid car battery was chosen for use in this project. However, car batteries are only designed for short-term, high-draw use, and tend to degrade over time if discharged below 50%. To avoid this limitation, a deep cycle lead-acid battery was chosen instead. Deep cycle batteries are designed for more long-term use, and can undergo deep discharges multiple times without degrading. This type of battery was not considered initially because of their high cost. However, it became apparent that they would be worth the price for their deep discharge capability, and also that there are some available on the market at a comparable price to car batteries.

CONNECTIONS The interface between the deep cycle battery and the solar panel involves a SAE to battery terminal connector, as well as a charge controller than prevents the solar panel from overcharging the battery. To distribute power, 16 gauge wire was selected for its max current limit of 3.7A. The total current draw expected is 2.8A, which allows for a sizable margin without adding more mass than necessary with the power cable.

3.4.4. Communications

Referring to the communication method trade study (Table 15), the Ethernet Local Access Network is a strong choice for this project's communication method. This method provides high data rate communication and has a low budgetary impact. While the wireless local access network offers a similar data rate and radio communication requires less integration work, both options have significant drawbacks and do not provide as good of an overall solution for the project. These criteria and constraints have resulted in the choice of a LAN for the project's communication solution.

The communication subsystem can be broken up into two main parts, communication between sensors, and the on board computer and communication between the instrument suite and ground station. Data gathered by the instrument suite is transferred to the ground station where it is stored for later collection by a user. Communication between the instrument suite and ground station is accomplished with a Local Access Network between the two on board computers. The LAN is formed by connecting the two via ethernet. Data will be stored on the ground station Pi with a 100 GB hard drive connected via USB. The Raspberry Pi 4 itself holds a 1.5 GHz, Quad-Core CPU with 4 GB of RAM and a 500 MHz VideoCore VI GPU which is more than sufficient to handle the external hardware interfaces (3 SPI sensors, a camera, and LAN connection).

HARDWARE Communication between the instrument suite and ground station is accomplished with a Local Access Network between the two on board computers. The LAN is formed by connecting the two via ethernet. Data will be stored on the ground station Pi with a 100 GB hard drive connected via USB. Data from all sensors is gathered via a SPI connection with the respective Raspberry Pi. The camera to Pi connection is accomplished via USB, which enables data transfer while simultaneously powering the camera.

SOFTWARE Data transfer between the instrument suite and ground station is accomplished via bash scripting which is called successively by the main loop. Preliminary testing has demonstrated the data transfer rate over ethernet to be approximately 216 MB/sec, well in excess of what is required for the anticipated data volume. Data will be acquired from the atmospheric sensor, GPS, anemometer, and IMU at 0.1, 0.1, 10, and 10 Hz respectively, while 10 images from the camera will be taken as fast as possible every 10 minutes. Preliminary testing has also demonstrated that the CPU and RAM usage of the Raspberry Pi will not be an issue given these current data cadences and, as a result, leaves ample room for increased data rates and image counts.

3.4.5. Microcontroller

The Raspberry Pi was chosen as the on-board and ground microcontroller. The Pi did have some drawbacks, as illustrated in the pros and cons table, however, it clearly stood apart from all other options within the trade space due to its superior processing power, and multiple interface ports. At this point in the project, the extent of software and computational needs are roughly known, but no upper bound has yet been set. As such, it is logical to use a board that is capable of interfacing with many data streams, and can process and transfer data from these streams quickly and efficiently.

This conclusion was reinforced within the microcontroller trade study (Table 18). The Raspberry Pi was the clear winner in the processing power, software integration, and hardware integration. As these were key considerations (justified in Table 16), the Pi won. The high price and power draw were not important enough to eliminate this option, as the board is key for successful data processing and delivery.

3.4.6. Data Calibration Method

Soil Moisture data would have been gathered before, during, and after the final testing period to provide useful information to the customer that could then be used to develop a soil moisture algorithm based off of IR images. Soil samples would be collected from five locations at the beginning and end of the test. These samples would be bagged, labelled, and weighed on site. The samples would later be baked in the oven until thoroughly dry and re-weighed to determine what percentage of the soil was water.

Throughout the test, soil moisture data collection stations (x5) would collect data in sync with the instrument suite's image collection. These data collection stations run independently and are made up of a Teensy 4.0 microcontroller, an RTC, and a SparkFun soil moisture sensor.

3.4.7. Additional Design Considerations

AIRBORNE STRUCTURES At the center of the design is the instrument suite and the balloon tether interface. A large portion of the critical components, namely the imaging system and the environmental sensors, sit within the instrument suite. The balloon tether interface, sitting atop the instrument suite, serves as the connection point for the tethers and the flight vehicle. The following figure shows the instrument suite with the interface attached.

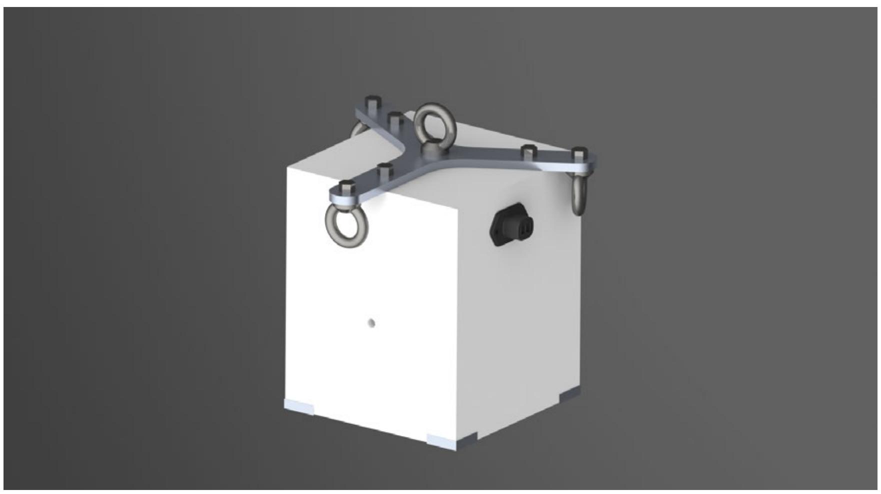

Figure 3: Instrument suite with interface attached

This image shows the two critical components in the air - that is the physical box itself, and the aluminum structure on top that serves as a connecting point for the flight vehicle and the tethers. The instrument suite is quite small - it is a cuboid measuring 5.8" x 5.8" x 7". This small size allows for all components to be fit inside while still maintaining a relatively low mass. The instrument suite exterior is composed of 3D printed PLA plastic. The bottom face of the cube has been left open, allowing for a clear 1/16" polycarbonate sheet to be placed over this open area. This polycarbonate face is attached using four corner brackets. The imaging system looks out of this face, allowing NIR pictures of the surface to be taken. Taking a look inside the instrument suite, as shown in Fig. 4, it is clear there is even less space.

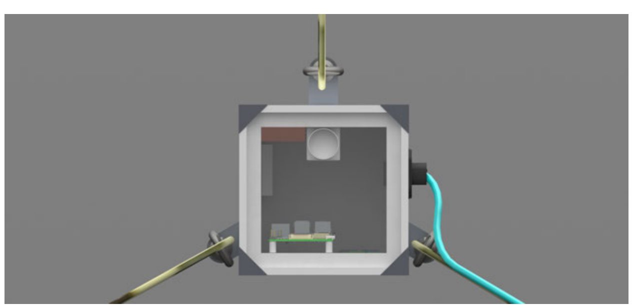

Figure 4: View inside the instrument suite

A large portion of the instrument suite's interior volume has been filled with extruded polystyrene. This thick layer of insulation ensures that the components maintain operational temperatures during flight and that no condensation will occur on the polycarbonate imaging surface. This condensation is covered later in the report. Also shown are all of the sensors and other electronics inside the instrument suite, including the camera, environmental sensors, battery, and Raspberry Pi.

The balloon tether interface has three outward protrusions, each with an eyebolt at the end. The tethers, which originate at the ground, connect to these eyebolts. In addition, another eyebolt sits at the center of this aluminum piece, serving as a connection point for the flight vehicle. Figures 5 and 6 show the connection points of the tethers and flight vehicle in more detail.

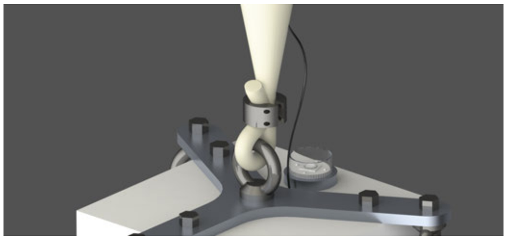

Figure 5: Balloon/Instrument Suite connection point

Figure 6: Tether/Instrument Suite connection point

Combining all of these design considerations together, the airborne components can be viewed as a whole system. The following image shows the integrated instrument suite, balloon tether interface, tethers, balloon, and a variety of electronics.

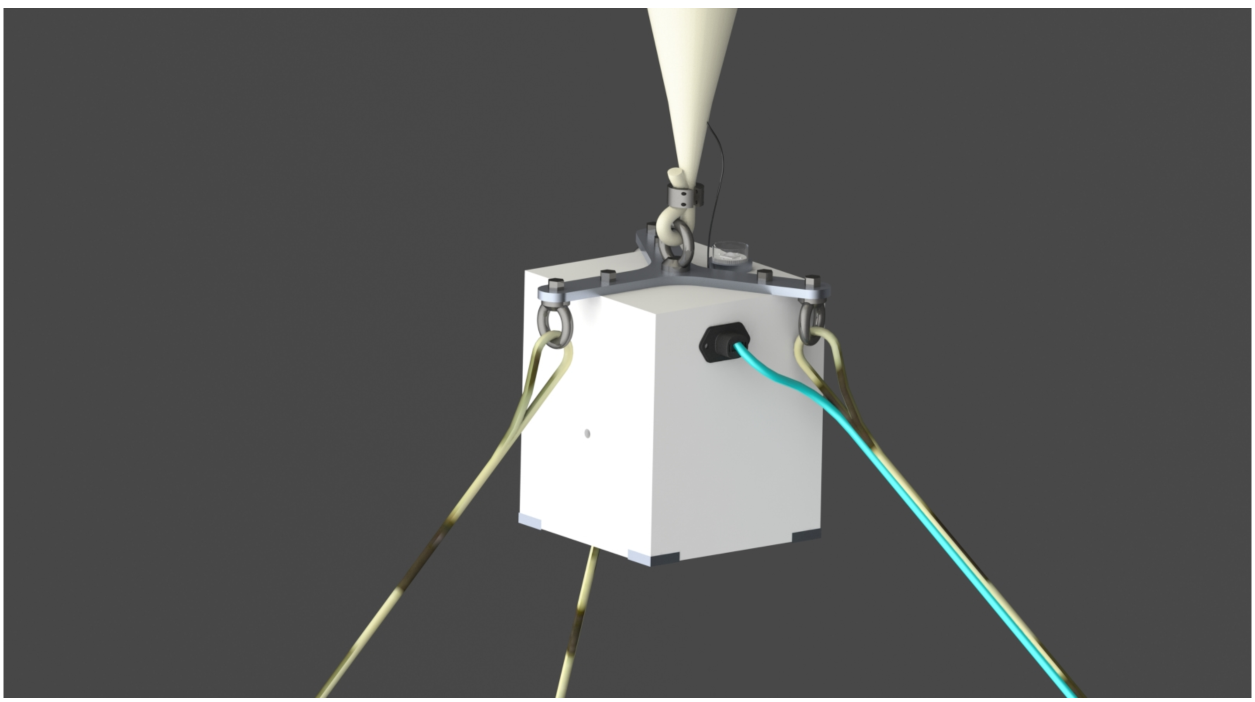

Figure 7: Integrated Airborne System

GROUND STRUCTURES The ground structures consists of three mooring stations that will be used to tether the flight vehicle, and a water resistant box that is used to house the power source and ground processor. The water resistant box is a simple 20" x 12" x 10" metal IP65 rated box which will house the battery and ground processor for protection from any light rain. The mooring stations consist of a 3/16" thick aluminum plate, two large steel tent stakes, a 1500 pound rated worm gear hand winch and two 50 pound sandbags. The worm gear winch is compatible with an electric drill which provides faster deployment and retraction times than tradition hand winches, and due to the perpendicular axis of rotation between the worm gear and winch drum, the tethers will not unspool under loading. The sandbags are placed on top of the aluminum plate to prevent lifting of the mooring station, while the stakes are used to prevent the mooring station from sliding. These mooring stations will be placed at a distance from the flight vehicle so that the nominal tethering angle when the balloon is inflated is approximately 45 degrees. Note that the selected tethers are a 7/64 in. Kevlar cord coated in polyester. These tethers have an ultimate tensile strength of 590 lbf and weigh in at only 0.003 lbm/ft. A CAD model of one of these mooring stations can be seen in Figure 8 below.

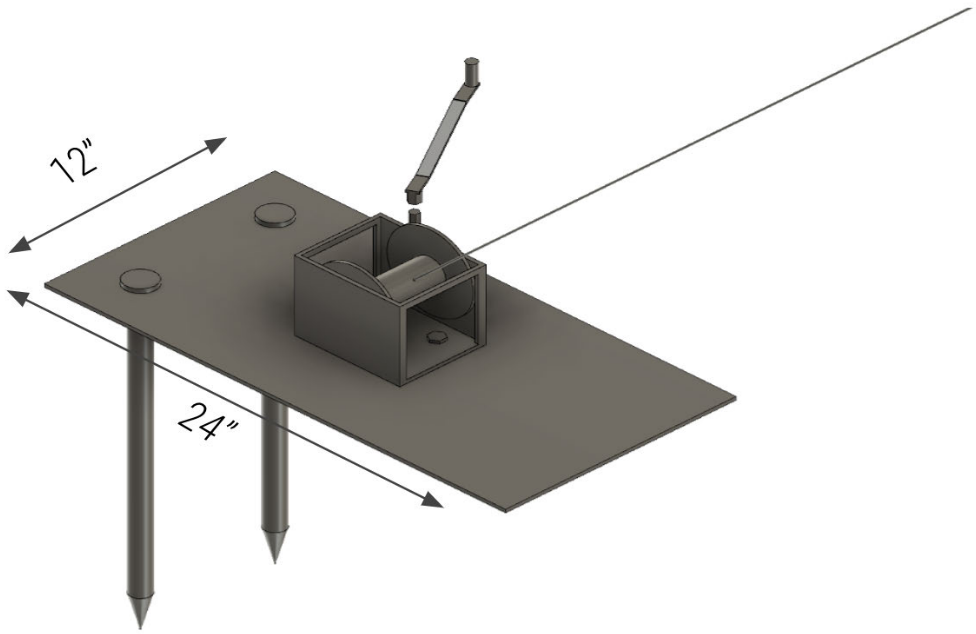

Figure 8: Mooring station used for tethering flight vehicle

ENVIRONMENTAL SENSORS After comparing the different environmental sensors, the SparkFun - BME280 atmospheric sensor was chosen. All atmospheric sensors investigated have very similar characteristics in terms of measurement and durability. The BME280 was chosen because this sensor has a lower price range and can easily be integrated with either I^2C or SPI protocol.

The measuring capabilities were also about the same for each sensor in regards to the IMU unit. Since the project is not heavily influenced by the accuracy of this sensor, an expensive and therefore more accurate sensor is not needed. This ultimatley led to the decision of SparkFun's MPU-9250; this sensor has a small board size and again allows for I^2C or SPI protocol.

When selecting a sensor to measure wind speed, the only viable options were the cup or vane anemometers as the other anemometers are outside of the allotted budget. Additionally, both cup and vane anemometers do not need to rely on the direction of the wind as the project is only concerned with the magnitude of the wind. Adafruit's cup anemometer was ultimately decided on, because it is small in size, cheap, and easily integrated.

REFERENCE POINTS The team initially chose to use IR stickers mounted to plates as reference points. After testing with the camera, reference points were found to be unnecessary and were discarded from the design.

RAPID DEFLATION DEVICE Due to design dependency and only one usable choice, a trade study was not conducted for the rapid deflation device. It is clear that the passive mechanical pressure relief device is not an option due to its cost not being within the budget of this project. These components also have a high chance of accidental engagement and leaking, both of which are not acceptable in this project. While the active electronic pressure release device has the lowest potential leak rate out of the three options, as well as a highly controllable deflation rate, it is simply too complicated of a system to include on the instrument suite for this project. For these reasons, the active balloon destruction device was selected. However, instead of essentially popping the balloon using a sharp object, a hot wire mechanism was selected. This hot wire works with an n-channel depletion MOSFET which keeps the resistive circuit of nichrome wire and a lipo battery open until a signal is sent to close it, at which point the nichrome wire heats to the melting point of latex and burns a hole in the balloon.

To ensure that this mechanism is not prematurely triggered, a two-step redundancy has been implemented. This begins with the Raspberry Pi onboard the instrument suite. The Pi will send an aliveness signal to an Arduino Nano, which will be powered by a 5V battery. The Nano will be continuously taking and comparing pressure data, looking for discrepancies. If the aliveness signal is lost (i.e. the deep cycle battery on the ground stops providing power to the Raspberry Pi) and the Nano detects a pressure differential, the MOSFET will be triggered by cutting a -5V supply to it, and the wire will heat up.

IMAGE ALIGNMENT The SIFT algorithm was chosen as it is a standard that is heavily used for image alignment within the field of computer vision. Other algorithms were either not well suited for this specific application, or took excessively long to run.

4. Manufacturing and Integration

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4.1. Manufacturing

4.1.1. Instrument Suite

As covered in the design process section, the instrument suite itself, from a manufacturing standpoint, is relatively simple. It is a 3D printed box that is hollow in the center with the bottom face missing. It also has several holes for cable connectors and bolts. For reference, the following figure shows just the instrument suite in all of its glory.

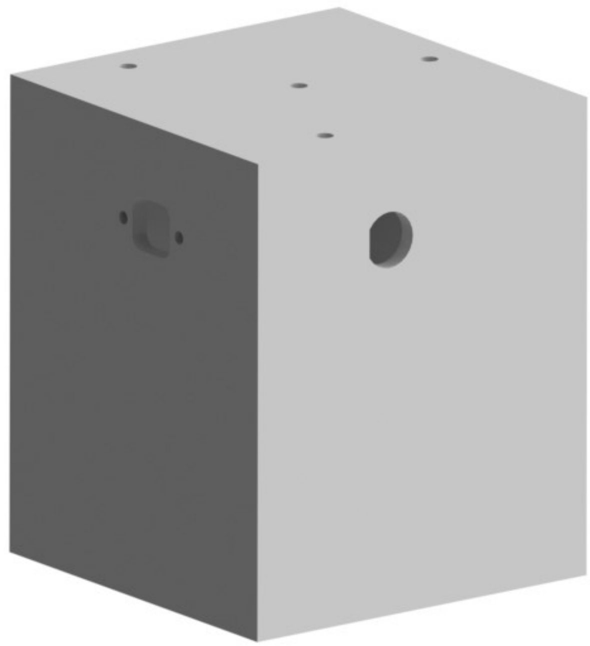

Figure 9: Instrument Suite

Manufacturing of this component was done primarily by a third party. This process was relatively simple: a part file containing the geometry (STL format) was uploaded to the company website and a variety of options were chosen. Due to concerns of mass and cost, PLA was selected material. The chosen 3D printing infill was 20% with a 100 μm layer height. This order was placed on February 7th and the box arrived on February 24th.

When the box arrived, the quality was questionable. The individual layers of the 3D print were visible and gave the box a rough texture, but this was expected as the largest possible layer height was chosen for cost's sake. The actual details of the print were slightly sub par. The interfaces for both the Ethernet and power connector had some printer error, resulting in an uneven opening. One screw hole on the top of the instrument suite was slightly off center; measurements indicated about 1mm.

These manufacturing errors called for some modification on the team's end to fix. These modifications were done in the machine shop at the Aerospace building. Correcting the off-center hole on the top of the box was simple; this just involved running the proper sized drill bit through the box in the correct position. Fixing the error in the interface holes required a lot of hand filing, which was time consuming, but posed the least risk to the instrument suite itself. Both manufacturing errors were successfully fixed, and allowed the interface components and fasteners to be properly installed.

4.1.2. Balloon Tether Interface

The balloon tether interface is the three-armed Al6061-T6 piece that is bolted to the top of the instrument suite. It allows both the tethers and the balloon to connect to the instrument suite. Further detail can be found in the design process section. The following figure 10 shows just the component for reference.

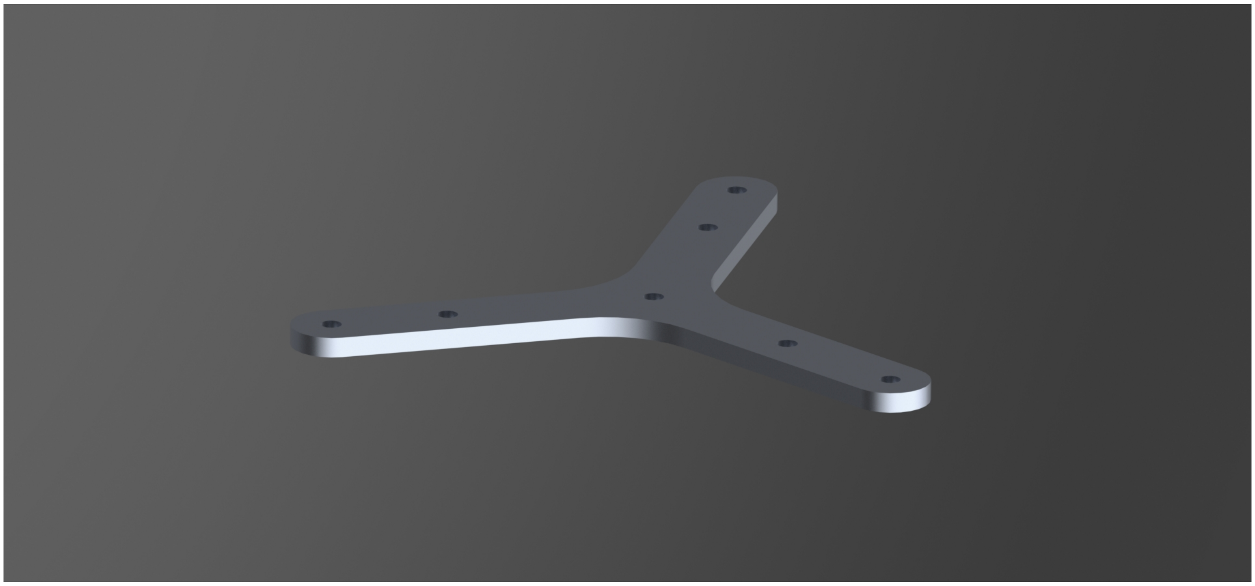

Figure 10: Balloon Tether Interface

Similar to the instrument suite, the interface was designed by the team but manufactured by a third party. This third party was the CU Precision Instruments shop. The choice to have the airborne structure manufactured by a third party was relatively easy to make. The geometry of the part itself is moderately complex, with varying lengths and angles throughout the piece, so it was decided that both for the sake of time and a lower chance of error, having an experienced third party manufacture the piece would be the best option. The Precision Instruments shop used a very large waterjet cutter to manufacture the piece. The original CAD part file was sent to them and they cut two interfaces from the 12" x 12" AL6061-T6 stock within the day. Two interfaces were cut in case either were to fail during testing.

There were no challenges involved in the manufacture of this piece. The Precision Instruments shop did a wonderful job; all edges were filleted and all exposed cut surfaces sanded down so the part both looked and felt fantastic.

4.1.3. Ground Structure

The ground structures consisted of three sections: a ground station, which housed data storage and the ground processor, the soil moisture probes, and the mooring stations, which tethered the flight vehicle.

The ground station was a COTS carbon steel electronics box that is typically used in construction projects. This box was selected as it was affordable, large enough to house the battery and various other electronics, and was water resistant. The COTS box also included a pre-fitted slot for the power and communications lines which would power and communicate with the instrument suite. Assembly of the ground station was not completed as it would have inconvenienced further testing of the power system and ground processor software.

Soil moisture probes were manufactured for the purpose of logging/storing soil moisture data throughout the duration of the flight. The probes' hardware consisted of a Teensy 4.0 microcontroller connected to a Sparkfun SEN-13322 soil moisture sensor to measure soil moisture content, a MicroSD adapter breakout board to store the data, a 9V alkaline battery to power all the hardware, and a voltage regulator between the microcontroller and battery. Aside from the soil moisture sensor prongs, all hardware would have been housed in 3D printed PLA housing to reduce contact with dirt/water. The following diagram describes the soil moisture data collection procedure.

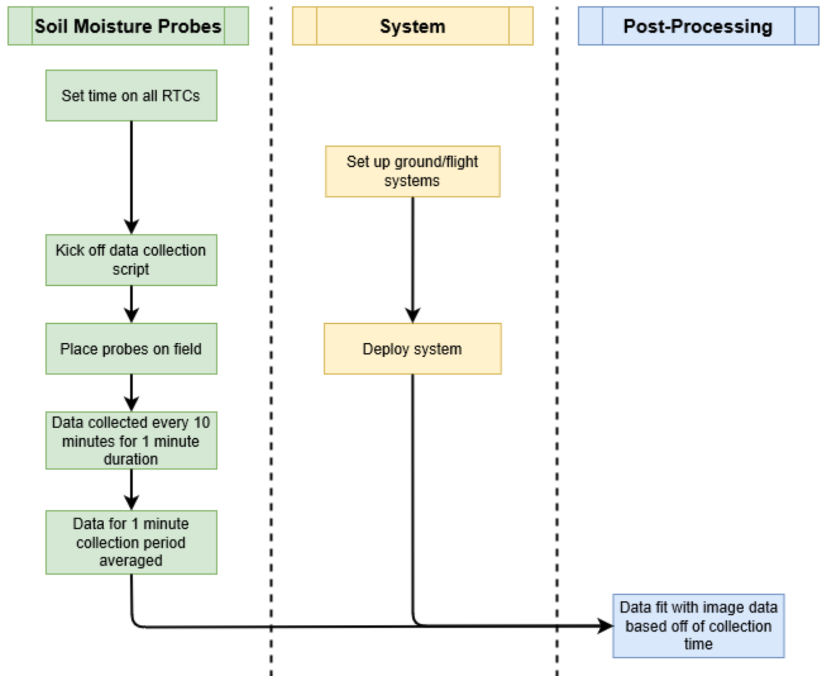

Figure 11: Soil Moisture Collection Procedure

The three mooring stations each consisted of an aluminum plate, two carbon steel stakes, and a COTS worm gear winch. Each plate had two loose fit 5/8 inch holes drilled at one end for placement of the 18 inch carbon steel stakes and three close fit 3/8 inch holes were drilled in the center of the plate for the winches. 7/64 inch Kevlar tethers coated with polyester were cut to 180 feet in length. This length provided a 9% margin when compared to the length required to reach the desired altitude, which would be enough margin to secure the tethers to the airborne structure and winches at either end. The full length tethers were not spooled onto the winches since 10 foot sections were used from small scale structural testing.

Overall the ground structure manufacturing and assembly went as planned. There were no significant challenges faced in the manufacturing and assembly of the mooring stations since the process was fairly trivial. As previously stated, assembly of the ground station COTS box was not completed for ease of subsystem testing, however no challenges were expected with nesting electronic and power components within the box. The soil moisture probes were designed to work "remotely", meaning that a major challenge was to keep the hardware powered. The team was not able to verify whether a 9V alkaline battery would be able to supply power for a 24 hour period.

4.1.4. Flight Vehicle

The balloon inflation system required only one component to be manufactured; the rest of the components were assembled from items purchased commercially off the shelf. To inflate the balloon, an adapter between the quick connect coming off the helium tank and the balloon neck had to be fabricated. This inflation adapter was first designed in Solidworks, and the raw material was then purchased from McMaster. For the full scale version, it was a 7.25 inch long, 2.5 inch diameter PVC rod. First, a through-hole was drilled through the center with a lathe, using a drill size of 7/16 inches. The holes on both sides of the tube were then tapped with a 1/4 inch NPT drill. The quick connect socket was then screwed on to one side of the tube. For the scaled version of the inflation adapter for the scaled balloon test, it was 5 inches long with a 1.3 inch diameter PVC rod. However, the rod was initially 2.5 inches in diameter, and a lathe was used to reduce the diameter. A through-hole was drilled with the same drill size, and the holes were also tapped with a 1/4 inch NPT drill. To inflate the balloon, the following components are required: (1) ¼" male NPT quick connect socket, (1) ¼" male NPT quick connect plug, (1) ¼" female to female NPT hose, (1) ¼" male NPT to nipple/nut CGA 580 regulator, (1) box of latex rubber bands, (1) PVC inflation adapter, (1) roll of electrical tape, (1) rappel ring, (1) locking carabiner, (3) 5 ft Kevlar mooring rope.

The quick connect socket and plug were used to quickly disconnect the inflation hose from the balloon neck without leaking, as the socket is self-sealing. The quick connect socket was connected to the fabricated inflation adapter. The NPT hose was connected to the quick connect plug on one side, and the CGA 580 helium tank regulator on the other side. The Kevlar mooring rope was secured to the hose at the quick connect to prevent the balloon from flying off. The other side of the mooring rope was wrapped around the helium tank. The regulator was then connected to the tank. When ready to inflate, the inflation adapter was inserted into the balloon neck, and rubber bands were used to secure the adapter to the neck. Once the balloon was inflated, the plug and socket were disconnected, and several rubber bands were used to tie two points on the balloon neck, one near the top of the neck, and one near the bottom of the neck. The neck was then passed through a rappel ring, and both sides of the neck were tied together with more rubber bands. A carabiner was locked onto the rappel ring and the top of the instrument suite. Finally, electrical tape was wrapped around the neck on top of the rubber bands, to further secure the neck from slipping. The full balloon inflation procedure can be found in the document, WIRMS Balloon Inflation Procedure.

4.1.5. Electronics and Power

The necessity for electronics was prevalent in both the instrument suite as well as the ground station. Within these branches of the project, COTS sensors were purchased while manufacturing was needed to integrate the sensors. For the COTS items: the whole project consisted of two Raspberry Pi 4's, an IMU (MPU-9250), an atmospheric sensor (BME-280), a NIR camera (EO-2223), an anemometer, a GPS sensor (MTK-3339), a LCD screen, an ADC (MCP-3002), two 5V buck converters, a 9V buck converter, and two fuses. The purpose of these components ranged from protecting the hardware to gathering and transmitting data.

The bulk of the manufacturing was implemented through integrating the sensors. Each of the breadboard compatible sensors were soldered onto a COTS solderable breadboard, and had to be correctly wired to receive power and communicate with the Raspberry Pi through SPI interface. There were two separate breadboards, one for the instrument suite, and one for the ground station. Each component on the breadboard was powered through the Raspberry Pi. The functionality of each sensor was confirmed by testing and receiving meaningful data. The team temporarily mounted the breadboard in the instrument suite using Velcro so that changes could be made easily if needed. For the final mounting, the team had planned to drill holes in the corners of the breadboard and screw it into the instrument suite using plastic standoffs to keep it off the instrument suite wall. The manufacturing for electronics was completed, with little to no complications.

The main components of the power production system consisted of a 300 watt solar panel, a 30 amp charge controller, and a 12V, 105 amp hour deep cycle battery. These components were all purchased off the shelf, and no manufacturing was required by the team. The power distribution system consisted of 200 feet of 16 gauge speaker cable that was purchased off the shelf, as well as several custom interfaces designed by the team. These interfaces include those at the instrument suite and ground station, as well as custom lug terminals at the battery itself. To distribute power to both the instrument suite and ground station from the battery, two lug terminal to battery clamp cables were purchased off the shelf. Holes were punched through the lug connectors to ensure their inner diameter would fit over the battery's terminals. For all preliminary testing, the battery clamps were left intact. However, for final testing, they would have been removed and the wires soldered directly to the respective instrument suite and ground station power lines.

To ease transportation and setup, it was desirable to be able to disconnect the 200 foot tether-run power line from the instrument suite electronics without having to open the instrument suite itself. To achieve this, a sealed Molex connector was selected to allow the team to plug power directly into the instrument suite. The Molex plug, receptacle, and crimps were purchased off the shelf. A Molex crimping tool provided by the Electronics Shop was used to assemble the plug and receptacle. This task proved to be difficult due to the tolerances set by the manufacturer. When inserted into the plug, the crimped wires would push the connector's locking mechanism forward rather than clicking into place. Additionally, the latch of the locking mechanism on the Molex receptacle had to be filed down in order for the plug to successfully be locked into place. After several failed attempts, a functioning Molex connector was produced and tested using the continuity setting on a multimeter. There were no further issues with this connector throughout testing.

Another issue that was encountered in the manufacturing process of the power distribution system was that of routing power to the Raspberry Pi's. Initially, a raw wire to a DIY micro USB connector was going to be used. However, the DIY micro USB connections proved to be too difficult to solder reliably with the tools available and current skill level of the team. As an alternative, COTS micro USB cables were acquired, and stripped to bare wire at one end. The first cable to undergo this proved to be insufficient for carrying enough current to the Raspberry Pi. A second, higher rated cable was then tested, and had no issue powering the Raspberry Pi. All other manufacturing tasks for the power distribution system were completed with no complications.

4.1.6. Software and Electronics

The software of this project consisted of the embedded system control of the instrument suite and auxiliary sensors as well as post processing of the data gathered. As a result of the Raspbian operating system used for both the Air Pi and Ground Pi, data gathering of the auxiliary sensors (IMU, atmospheric sensor, GPS, and anemometer) was programmed in Python 3.5. For each of these sensors, their respective Python packages to read data from the Raspberry Pi through the I2C and SPI protocols were used. Control of the basic functions of the EO-2223 camera was also obtained with the embedded linux distribution of the IDS camera management API which was interfaced with the Pyeye package (a Python wrapper for this API). Upon the arrest of manufacturing, the team had the ability to take and save NIR pictures with automatic exposure and white balance through the Raspberry Pi, fulfilling the relevant functional requirements. The teams goals proceeding the current status were to collaborate with the client ASTRA on picking manual values for the camera's white balance and shutter speed as well as to gain access to the camera's internal temperature sensor. Both the Ground Pi and Air Pi followed the same driver code written in Python 3.5 to combine the necessary data retrieval scripts for the sensors (and the camera for the Air Pi) as well as facilitate the other main functions such as data aggregation and communication between the two RPis. Due to the necessity of needing to run multiple functions at the same time (e.g. collecting data from the IMU at the same time as the photo collection process), multithreading was employed in the main script which was justified by initial research that all of these processes were thread safe. However, perhaps due to global interpreter lock of the Python programming language, unexpected behavior was encountered with the data collection of the IMU when multi-threaded.

The other main function controlled by the main driver was the communication between the two RPis. Communication between the Ground Pi and the Air Pi was handled via bash scripting. The bash script was called temporally within the main loop of the system. The script looked for new files that were created on the Air Pi since it was last called and downlinked and saved those files to the Ground Pi. The post processing software had three main applications: aligning images relative to an ideal baseline image, overlaying the images with a 7"x7" on ground grid, and analysing the average and standard deviation of the pixel values within each grid. Images were saved to a local folder, and pixel values were stored as an hdf5 file and saved in the same location. The software was programmed in Python 3.5, and the image alignment utilized the SIFT algorithm through the opencv package. Given more time, the grid overlay would have had an accompanying hdf5 file with the GPS location of each pixel. This would have been achieved using the on ground GPS and known North orientation of the image through an on ground indicator. Rotation matrices and a known pixel length were being used to extrapolate the relative coordinates of all pixels.

4.2. Integration

4.2.1. Airborne Structures Integration

With all of the airborne structural components completed, the integration step began. The first step in this process was attaching the balloon tether interface to the instrument suite. This was done with three 1/4"-20 bolts. These bolts ran through the top of the instrument suite, with rubber washers in between to act as a waterproofing barrier. An appropriately sized nut on the inside of the instrument suite secured the bolt in place. With this completed, the eyebolts and their corresponding nuts were attached to the three arms of the balloon tether interface. The final eyebolt, which sits in the middle of the instrument suite's upper surface, was attached using a rubber washer and a nut on the inside of the instrument suite.

Next, the insulation was cut to size and placed in the instrument suite. 1/2" extruded polystyrene was cut to size and placed on all faces of the instrument suite. Although the cutting of the polystyrene technically was a manufacturing process, it simply involved using a box cutter and posed no issue. For that reason, it was omitted from the manufacturing section. All insulation stayed in place because each piece was slightly oversized, allowing a friction fit between the instrument suite and other insulation piece to keep it in places. With all of the structural components assembled, a thin layer of white enamel spray paint was sprayed on the exterior of the system. This would provide a light barrier against scratches, water, and dirt, as well as it would reduce the albedo of the instrument suite, reducing temperature fluctuations during flight. The only structural component not integrated at that point in time was the clear polycarbonate face. This waited until after the integration of the electronics, which will be covered in the next section. The polycarbonate face was held to the instrument suite using silicon adhesive and corner brackets.

4.2.2. *Ground Structures Integration*

The Mooring Station integration process was trivial. The COTS worm gear winches were bolted to the aluminum plates using 3/8 inch stainless steel bolts and nylon lock nuts. The 10 foot sections of tether cut for small scale testing were then spooled onto the winch drums using an electric drill. The two carbon steel stakes and two 50 lbs sand bags were placed each time the mooring stations were set up for any subsystem testing.

One of the five soil moisture probes was integrated and undergoing testing prior to assembling the others at the time of the halt. The CAD for the soil moisture probe is shown in figure 12 below.The Teensy 4.0 is shown in green, the SD card module is shown in blue, the battery in yellow, and the soil moisture probe in orange.

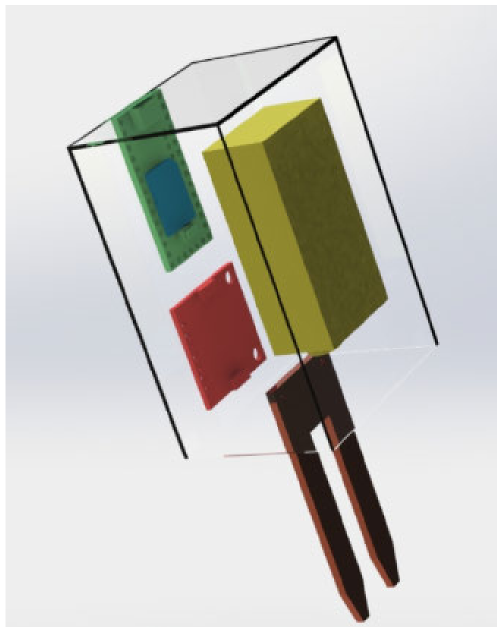

Figure 12: Soil Moisture Probe CAD

4.2.3. *Electronics and Power*

The integration of the electronic components was accomplished in an iterative process. The components of the ground station and instrument suite were integrated into their respective systems individually. Once functionality of each system was confirmed individually, they were integrated into their respective hardware structures. At this point, the integration of the two systems into one would have occurred via the hard-line Ethernet connection. However, this step of the integration process did not occur.

The integration of the power supply and distribution components began with the solar panels, charge controller, and deep cycle battery. These components were connected via the MC4 and battery clamp connectors that came with the solar panels. Power from the battery to the instrument suite and ground station was routed via the lug terminal to battery clamp connectors discussed in the previous section. Power to both the instrument suite and ground station was then fed through a fuse to protect against current spikes. The fuses used were integrated into a COTS Sparkfun fuse breakout board with screw terminals, which allowed for easy assembly and disassembly. Power in the instrument suite was then fed through a 5V buck, while power in the ground station was split between a 5V buck and a 9V buck. The 5V bucks used were already integrated onto a heat shrinked board, with raw wire on either end. Thus, integrating these bucks into the power distribution system was simply a matter of soldering and heat shrinking wires. The 9V buck did not come pre-integrated, and therefore was used in conjunction with a breadboard throughout testing. For final testing, all components of the ground station, including the deep cycle battery, would have been placed into the weather resistant carbon steel box. The diagram below shows how all of the electronic components of the instrument suite and ground station were integrated together.

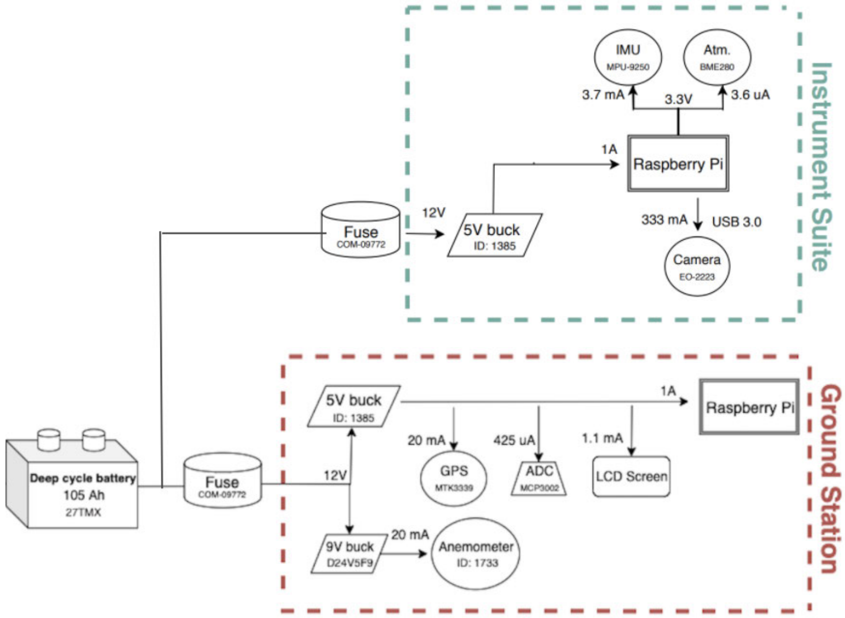

Figure 13: Power distribution diagram

5. Verification and Validation

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5.1. Software

5.1.1. Image Alignment

DR7.3.1 - Images shall be aligned in post processing.

DR4.2.1 - The imaging system shall produce images with a resolution of 7x7 square inch per pixel at flight altitude

Model: The SIFT algorithm was used for image alignment. This is an existing and standard computer vision algorithm. At a fundamental level, the algorithm identifies maxima/minima pixels, eliminates low contrast points, and removes any areas with a high edge response (i.e. straight lines). When implemented across similar images, the same keypoints will be identified. The algorithm creates a histogram and orientation chart for each point, and aligns the image by matching the location and orientation of each keypoint. The point of this test is to validate DR 7.3.1.

Test Overview: Images were taken with the NIR camera from the Aerospace Building top floor of the field directly behind. This acted to mimic the expected imaging conditions and subject. The camera was then rotated and translated while taking images to simulate the most extreme blur/movement that would be seen during flight. The camera was handheld and angles were measured using a protractor. Images were then captured while the camera was gently shaken. It should be noted that the expected perturbations were very small, so using an imprecise setup gave greater movement than expected. These images were then run through the image alignment software and inspected to ensure that the final product was usable.

Test Results: The images captured, even though at translations and angular displacements greater than expected, were correctly aligned and usable for customer data. Thus, the test and the code it validated were successful. Figure 14 shows the baseline image capture. Figure 15 shows one of the rotated and translated images. Finally, Figure 16 shows the aligned image. Note that the key features overlap across the baseline and aligned images.

Figure 14: Baseline Image

Figure 15: Rotated Image

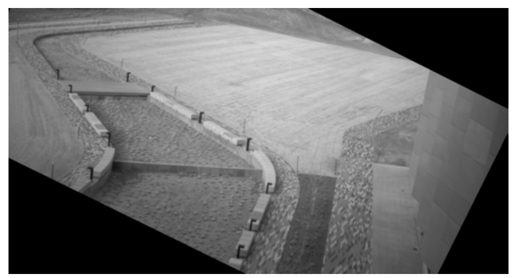


Figure 16: Aligned Image

Measurements: The only measurements recorded were the NIR images from the EO camera. These images had a resolution of 2048x1088 pixels.

Verification: The verification process was conducted visually, as success was binary. Alignment failure was very obvious and only occurred when there was extremely little to no overlap with the baseline image. Figure 17 shows the baseline image. Figure 18 shows the image which failed to align. Note that there is no overlap in subject between the baseline and captured image. Finally, Figure 19 shows the output of a poor image. As such, the test was binary. The alignment test was passed in all cases where the subject overlapped. This condition was expected through the pointing model.

Figure 17: Baseline Image

Figure 18: Original Image

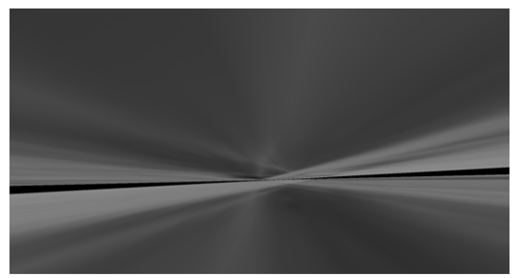


Figure 19: Unsuccessfully Aligned

Validation: Since this test was passed in conditions beyond expected, it was successful. This validates DR 7.3.1 Images shall be aligned in post processing. Further, DR4.2.1: The imaging system shall produce images with a resolution of 7x7 square inch per pixel at flight altitude was verified through inspection of camera resolution and imaging area. This was a simple calculation using resolution and predicted image area.

5.1.2. Instrument Suite and Communications Integration

DR6.1: Data transfer shall be autonomous.

DR7.5: All data downlinked from the instrument suite shall be stored on the ground station processor.

Model: Based on preliminary research, it was anticipated that the data transfer rates between the Air Pi and Ground Pi could match the amount of data collection rate by the Air Pi such that the Ground Pi could theoretically present the gathered data in a live feed fulfilling design requirements 6.1 and 7.5. It was also anticipated that the CPU usages of the both Air PI and Ground Pi would never reach 90% of the max CPU usage such that behavior of the camera could remain consistent. Since both the Air Pi and Ground Pi have 4GB of RAM, RAM usage was deemed unnecessary to test due to the relatively small amount of data being transferred at a time.

Test Overview: To complete a performance test of the fully integrated instrument suite, the Air Pi was fully connected to the IMU, atmospheric sensor, EO-2223 camera, and an idle Ground Pi. Since the functionality of the Ground Pi's main script was significantly less than that of the Air Pi, CPU usage of the Ground Pi was not considered. Power was delivered to the Air Pi and Ground Pi through the bench power supplies located in the electronics lab of the AERO building and current draw was measured from the electronics lab multimeters. CPU usage was measured every 0.5 seconds and corresponding labels for before, during, and after each functional step were displayed.

Measurements: The key measurements recorded were the CPU usage, the data rate, and the current draw. The CPU usage was the primary metric used to evaluate success. The data rate was used to verify that the achievable data rate was high enough to transfer all data within the 10 minute window. Finally, the current draw was measured to ensure the instrument suite electronics could provide sufficient power to the Pi during maximum operation.

Verification: Under operational conditions, the CPU of both the Air and Ground Pi did not exceed 90%, which was the model driven limit on performance which allows us to fulfill design requirements 6.1 and 7.5. As such, performance of the software and hardware integration were successfully verified.

Validation: One important consideration for the CPU usage measurements comes from the fact that running the Psutils python package to measure CPU usage takes in itself a non-negligible amount of CPU usage. As a result, without this diagnostic tool, it was expected to see an even smaller load on the Air Pi. In terms of the data transfer rate, one limitation of the testing method was that data was transferred from the internal SD card of the Air Pi to the internal SD card of the Ground Pi. In reality, the data would have been saved onto an external hard drive connected to the Ground Pi, so the data transfer rate would most likely be thresholded by the hard drive write times.

5.2. Structures

DR1.3 - The flight vehicle shall maintain an altitude between 100 - 150 feet for flight duration.

DR1.4 - The flight vehicle shall be secured to the ground structures.

DR1.4.1 - The tethering structural elements shall each have their own factor of safety of 3 for failure under inclement conditions.

Model: The structural model consisted of calculations for the mooring stations and balloon tether interface to determine the factors of safety against yielding for the various failure modes of the components making up each structure. The calculations were done under a worst case loading scenario, that being a 40 mph wind aligned with one tether, causing the other two tethers to be in slack. Given the lift of the balloon and the drag force with 40 mph winds, the resulting calculated tension would be 403 [N]. Based on the pointing model which was developed, the tether angle would reach a steady state 25 degree angle from horizontal instead of the nominal 45 degree angle. The free body diagrams for the balloon tether interfaces and mooring stations are shown in figures 20 and 21 below.

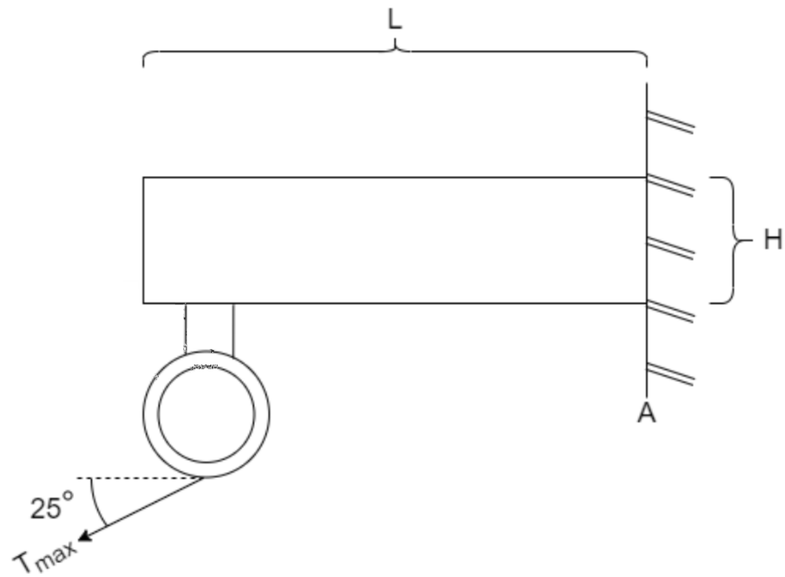


Figure 20: Balloon Tether Interface FBD

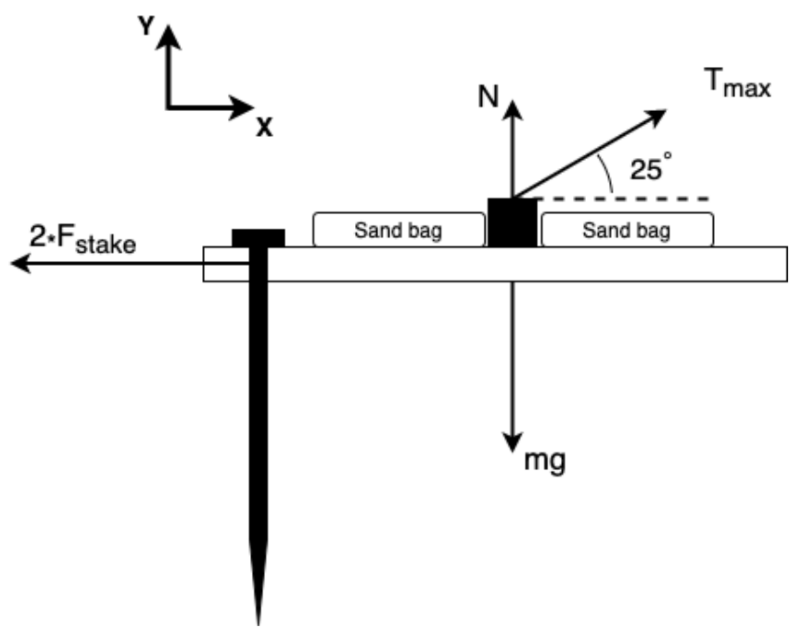


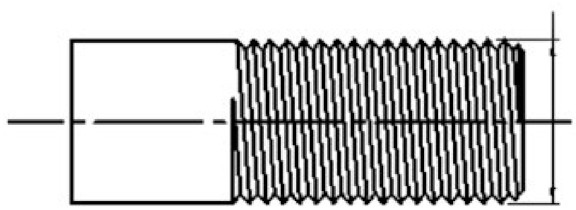
Figure 21: Mooring Stations FBD

The first failure mode to cover is failure of the beam itself in tensile stress. This equation is relatively simple, and finds the stress in the beam using the force normal to the beam acting over the cross sectional area. At worst case, where the maximum operational condition value for wind acts directly along the tether, the beam itself experiences a force of 2.25 MPa. The yield strength of 6061-T6 aluminum is 276 MPa. This means in tensile loading, the beam has a factor of safety of 123. The next failure model is a flexural or bending failure. Under too large a load, the beam would crack of buckle, causing irreversible damage. Using a basic beam bending equation, the load due to bending was found to be 46.1 MPa. Since the aluminum is assumed linear elastic and isotropic, the yield stress for bending is also 276 MPa. This means in bending, the beam has a factor of safety of 6. Finally, the thread failure of the eyebolts is analyzed. In this mode, the force acting on the eyelet body would be greater than the force the threads in the aluminum or eyebolt shaft can handle, causing a thread out failure. The following diagram shows an area correction based on the thread diameter and the number of threads per inch. This will find the total area that a normal force acts on for the threads, allowing failure calculations.

A_t = tensile strength area of screw thread.

D = *Basic major diameter*

n = Number of threads per inch



Equation:

$$A_t = 0.7854\left(D - \frac{0.9743}{n}\right)^2$$

Figure 22: Thread area correction

From this thread area, it is possible to calculate the total stress in the threads. For the selected eyebolts, the stress was found to be 1.39 MPa. For the required thread depth, the maximum allowable stress is 23.4 MPa. This gives a factor of safety of 16.8, meaning there will be no thread out failure.

The normal force on the mooring station is computed to be 298.5 N, which insures that the flight vehicle will not be capable of lifting any mooring stations off the ground. The Kevlar cord selected to be used for tethering the flight vehicle has an ultimate tensile strength of 2624 N and the worm gear hand winch is rated for a maximum load of 6672 N. The maximum load rating for both the tethers and winch are provided by their respective manufacturers, and using this information the factors of safety for the tethers and the worm gear winch are computed to be 6.5 and 16.5 respectively. Additional failure modes considered were shear failure of the plate, shear failure of the stakes, shear failure of the bolts which hold the winch to the plate, and a thread out failure of the bolts. The yielding stress, expected stress and factor of safety for these additional failure modes considered are shown in the table 22 below. Given these results the balloon tether interface and mooring stations were not expected to undergo any yielding under the worst case expected loading.

Table 22: Computed Factors of Safety for Miscellaneous Mooring Station Components

Component	Yield Stress	Average Expected Stress	**Factor of Safety**
Aluminum Plate	159.4 MPa	0.151 MPa	**1055**
Steel Stake	236.7 MPa	0.923 MPa	**256**
Stainless Steel Bolts (thread-out failure)	124.1 MPa	1.71 MPa	**73**
Stainless Steel Bolts (shear failure)	124.1 MPa	1.00 MPa	**124**

Test Overview: To conduct the structural testing, a pulley was first tied off to a fixed object so that a constant 90 lbs load could be applied through the balloon tether interface, tether and mooring station. A single mooring station was then set up at a measured distance from the balloon tether interface so that the 25 degree angle between the tether and horizontal could be achieved. The Kevlar tether connected to the worm gear winch was knotted to the balloon tether interface, and a second tether was used to connect the balloon tether interface to the 90lbs load through the pulley. The diagram shown in figure 23 below depicts the final test setup for the structural testing.

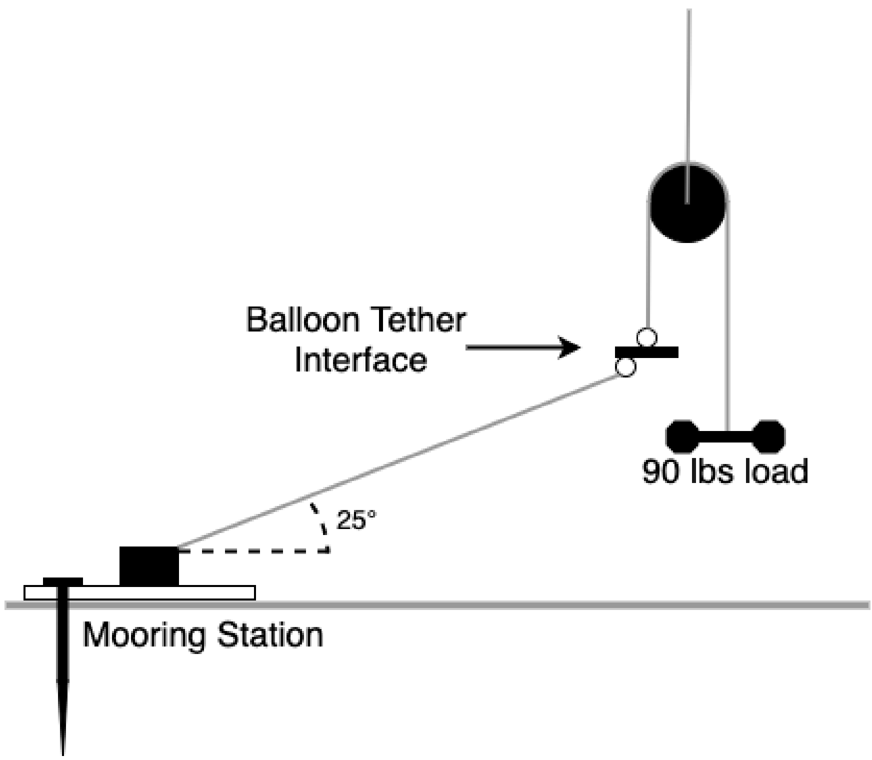


Figure 23: Structural Test Setup Overview

Measurements: Direct measurements for the structural testing were not taken, however each component was visually inspected for any damage or yielding under the applied load. In addition to the visual inspection, a straight edged bubble level was used to evaluate if any bending of the balloon tether interface occurred.

Verification: The structural testing was overall successful as no components experienced any yielding deformations. The major concern from the model showed that bending of the balloon tether interface was of the highest concern. Upon close inspection of the bubble level, it was confirmed that the balloon tether interface did not undergo any bending deformations at the predicted worst case loading scenario. Figures 24 and 25 below depict the results from the structural testing that was conducted.

Figure 24: Structural Test Results

Figure 25: Structural Test Results

Validation: The structural testing performed validates that the mooring stations and balloon tether interface designed are capable of meeting their respective design requirements. The subsystem testing proved that the mooring stations and balloon tether interface would be capable of securing the flight vehicle to the ground structures under the predicted worst case loading, and would meet a factor of safety against failure of 3 for the tethering elements. Thus, the balloon tether interface and mooring stations have satisfied design requirements 1.4 and 1.4.1. Since the structural elements of the project are capable of securing the flight vehicle, it is clear that the mooring stations and balloon tether interface will also be capable of limiting the flight vehicle's altitude to below 150 feet; thus the structural elements have satisfied design requirement 1.3.

5.3. Instrument Suite Dynamics & Camera Pointing Model Test

DR4.2 - The imaging system shall produce images of the ground with dimensions of 300 square feet

DR9.2 - Soil moisture data shall be collected over the testing area of 300 square feet

Model: In the fall of 2019, the team developed a discrete element model inspired by Nahon's 1999 paper on tri-tethered balloon dynamics. The balloon/tether structure is subject to a variety of forces: the Earth's gravitational pull, drag, and internal damping. Each tether is modeled by discrete elements bound by two nodes along each tether as seen in Fig. 26. To develop the model in full, several assumptions about the system had to be made. A few of these assumptions can be seen below.

1. Balloon experiences no deformation and modeled as a sphere occupying the same place as the instrument suite
    - The spherical assumption is to simplify the model
    - Balloon deformation would make the team quantify the elastic response of the latex balloon, greatly increasing complexity
2. Tether drag is ignored
    - Although the tether drag is ignored, the team still calculated maximum drag possible on all tethers as a percentage of balloon drag. This was used to understand how much drag was being ignored
3. Drag coefficient of balloon is constant
    - The drag coefficient used was that of a sphere (assumption #1)
    - The drag coefficient is dependent on Reynolds number and no experimental data points could be found
    - Mean Reynolds number of 2e6
4. Cross sectional area of tethers are constant
    - A Poisson's ratio and initial guess for cross sectional area would be needed, both unattainable

With these assumptions made, the model was ready to be developed in full.

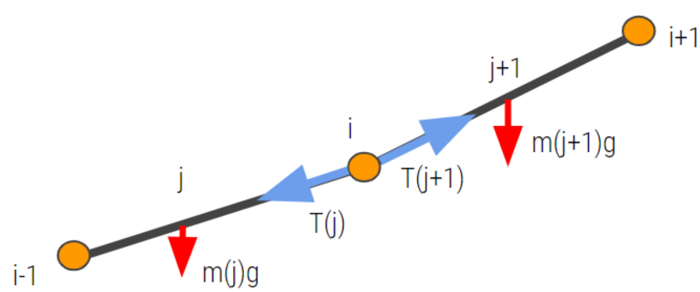


Figure 26: Free body diagram for a the ith node

The model allowed the team to predict the dynamics and pointing of the instrument suite due to wind loads on the latex balloon. In practice, the images taken by the NIR camera would be supplemented with on ground soil moisture measurements from the soil moisture probes [DR9.2]. The NIR images could then be calibrated and mapped to the on ground soil moisture readings. This required the team to image the same plot of land consistently throughout the duration of the flight. The instrument suite dynamics and pointing model predicted that the NIR camera in the instrument suite could image the same 300 sqft plot of land [DR4.2] under maximum operational winds of 20 mph. In the spring semester the team set out to validate the pointing model developed in the fall semester.

Test Overview: To validate the instrument suite dynamics and pointing model the team would have set up a small-scale version of the tri-tethered balloon system. The small-scale setup would have included:

1. Mooring stations
2. NIR camera
3. Airborne structure
    - Instrument suite
    - Balloon-tether interface

4. Kevlar tethers
5. Ethernet and power cables

The large-scale stands at a height of 118 ft while the small-scale system stands at 7 ft and would be assembled in the aerospace high bay. A scaled down imaging area would have been drawn beneath the instrument suite prior to applying any loads to serve as a benchmark for the NIR camera.. The imaging area would be scaled down to preserve maximum turning angle allowed from the full-scale model $\theta_{TA} = 5.85^o$. The net lift would have been scaled to account for shorter tethers, Ethernet cables, and power cables. The new net lift is associated with a specific balloon diameter. The new balloon diameter would have been used to calculate a maximum drag component. Ultimately the net lift and drag component would be added to create a force vector on the system. To model the force vector, the team would have used a series of weights and a pulley system suspended from the ceiling of the aerospace high bay to match the magnitude and direction of the force vector on the instrument suite.

Measurements: Once the load is applied, the team would have measured the angle made by the instrument suite and the ground using a protractor and an IMU on board the instrument suite to validate that angles predicted by the model were accurate. Additionally images would have been taken of the ground to validate that the camera FOV was modeled appropriately.

Verification: This small-scale structure test would have verified that the instrument suite dynamics and pointing model produced accurate results. By comparing the predicted angle from the pointing model and experimental data, the team would have felt confident with the instrument suite dynamics and camera pointing when the full system would have been implemented.

Validation: With the model validated the team would have ensured that design requirement 4.2 would have been met and that the soil moisture data could supplement the NIR camera imaging data.

5.4. Flight Vehicle Diffusion Test

DR1.3.1 - The flight vehicle shall maintain a constant altitude in the acceptable range plus or minus 10 feet.

FR2 - The flight vehicle shall be capable of operating in the air for 1 day.

DR2.1 - The flight vehicle shall be provided enough propellant to withstand a day long flight.

DR2.2 - The flight vehicle shall have enough propellant to stay at an altitude between 100 - 150 feet for a day long flight.

Model: Leakage of the propellant gas through the balloon skin is possible, therefore the permeation and diffusion of the propellant through the rubber membrane was analyzed. The permeation and diffusion of gases through solids vary with type of gas, material, temperature, and pressure. The objectives regarding diffusion and permeation analysis are as follows:

1. Time for a certain percentage of the propellant to leak through the balloon membrane via diffusion.
2. The change in volume over time of the balloon.

Diffusion is net movement of molecules from a region of higher concentration to a region of lower concentration, and is driven by a gradient in concentration, measured in m^2/s. A particular partial differential equation, known as Fick's second law, was used to calculate diffusion. The following assumptions were then made:

1. Before diffusion, any of the diffusing solute atoms in the solid are uniformly distributed with the concentration of C_0.
2. The value of the distance x at the surface is zero, and increases with distance into the solid.
3. The time is taken to be zero the instant before the diffusion process begins.
4. Natural latex rubber is incompressible.

The boundary conditions can then be stated as:

For t = 0, C = C_0 at $0 \leq x \leq \infty$

For t >0, C = C_s at x = 0
C = C_0 at x = ∞
Applying the boundary conditions yields the following solution,

$$\frac{C_x - C_0}{C_s - C_0} = 1 - \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \tag{1}$$

The volume of the balloon before and after is set as an equation, and the final thickness solved for.

$$4\pi R_0^2 t_0 = 4\pi R_f^2 t_f$$
$$t_f = \frac{R_0^2 t_0}{R_f^2} \tag{2}$$

The time it takes for the required amount of propellant to diffuse through a certain thickness of the balloon can then be found. Time can be solved for by rearranging the solution to Fick's second law.

Test Overview: The objective of this test was to validate the diffusion model with a scaled version of the balloon. The balloon needed to demonstrate the ability to withstand a 20 hour flight duration with temperature fluctuations. The balloon was inflated in the High Bay to the desired lifting force of 4 lbs using a force gauge, and a meter stick was propped up next to the balloon. A GoPro camera was set up on a tripod to take photos of the balloon during the entirety of the test. A temperature gun was also present during the test to take the skin temperature of the balloon.

Figure 27: Team member next to inflated scaled test balloon

Measurements: Three measurements were recorded during the 20 hour experiment period, at an interval of every 30 minutes from start to end. The lifting force was recorded by reading the scale, and balloon skin temperature was recorded using the temperature gun, and a photo was taken using the GoPro.

Verification: This test provided information on the helium diffusion rate through the skin membrane of the balloon.

The test was performed starting right after TRR, and lasted around 54 hours until it was taken down manually. The performance of the balloon exceeded the predicted model by lasting twice as long and losing only 25% of lift. The balloon lasted 34 more hours than the expected 20 hours. The results indicate that diffusion should not pose a significant threat to the project, and that the team could now test diffusion, payload handling, and the ARDD device on the larger balloon. However, the balloon would not be able to stay up for a week, per a higher level of success. Nevertheless, being able to stay up for at least 20 hours satisfies the functional require FR2.

Validation: The collected photographs needed to be analyzed for information regarding the change in volume of the balloon with temperature swings. A script to find the correlation between change in volume, lift, and rate of diffusion was in the process of being written and tested. The script was expanded from code originally created by Duncan McGough. The code allowed user tracing of an object, and with a corresponding unit of measure, the volume of the traced object would be calculated. If the team would have been able to progress further in the project, the photographs of the balloon would be processed using the MATLAB script to find the change in volume over time and with corresponding temperature swings and lift measurements. Using this method, the team would have verified FR 2 and all the requirements below, as well as DR 1.3.1. Some concerns about the model are the human error in tracing out the object as well as the accuracy of the unit measurement which is also traced out in the image. Since the diffusion rate is very slow, it would be difficult to obtain precise measurements of volume decrease with the possible aforementioned complications.

5.5. Flight Vehicle Neck Test

FR2 - The flight vehicle shall be capable of operating in the air for 1 day.

Model: Because the expected payload weight is higher than the manufacturer's recommended weight, analysis of the balloon structure needed to be done to make sure it was capable of holding the payload without breaking. This corresponds with the requirement FR2, as stated above. Before doing any calculations, some assumptions need to be made and the given information stated.

1. The three-dimensional shape of the inflated balloon is a sphere.
2. Payload mass does not change over the course of the flight.
3. The mass of the propellant gas is constant and does not change even if the volume changes.
4. Launch and flight parameters are calculated with Boulder atmospheric conditions.
5. The coefficient of drag of the sphere is 0.2, which corresponds to a Reynold's number of 2e6
6. The uninflated balloon body thickness is 2 mm, and is 4 mm for the neck.
7. Natural latex rubber is incompressible.

The objective of the stress analyses are to prove that the balloon structure will not break upon inflation and flight.

First, the volume of the balloon needs to be calculated. Using the diameter calculated previously in the thermal analysis, the volume of the balloon using $V = (4/3)\pi r^3$ is found. The gas mass can then be calculated using $m_{gas} = V_{balloon} \cdot \rho_{propellant}$. Using Archimedes' principle, the lifting force of the balloon is

$$L_{actual} = (V_{balloon} \cdot \rho_{ambient}) - (V_{balloon} \cdot \rho_{propellant}) \cdot g. \quad (3)$$

To find the net lift of the balloon, the gas weight and the payload weight is subtracted from the actual lift, $L_{net} = L_{actual} - w_{propellant} - w_{payload}$. The payload mass is approximately 11.1 kg. For these analyses, a worst case 20 mph wind condition is added, which has a vector straight up, as this will cause the most stress on the balloon. The drag force can be calculated using $F_{drag} = 0.5 \cdot \rho_{ambient} \cdot V_{wind}^2 \cdot C_d \cdot A_{balloon}$, where $\rho_{ambient}$ is 1.0 kg/m^3 due to being at Boulder elevation, and $A_{balloon}$ is the surface area of the balloon. C_d is chosen to be 0.2 because the Reynolds number the system will experience is expected to be approximately 2 million.

Table 23 presents the summary of the calculations for the maximum, nominal, and minimum diameters for the balloon, and associated performance specifications. All the safety factors are high, meaning the balloon should be able to reach the objective of not breaking apart upon inflation or flight. It should also be noted that the manufacturer has recommended that the balloon not be reused after one flight, due to degradation of the balloon material. However, through the analysis, the team can be assured that FR 2 can be achieved.

Table 23: Summary of balloon analysis

Diameter [m]	3.68	3.50	3.44
$V_{balloon}$ [m^3]	26.09	22.45	21.31
m_{gas} [kg]	4.67	4.02	3.82
L_{actual} [N]	210.16	180.81	171.67
L_{net} [N]	61.85	32.50	23.36
$t_{balloon}$ [mm]	0.500	0.5528	0.5722
FoS M1, Inflation	7.81	10.04	10.95
FoS M1, Flight	26.52	55.87	80.50
FoS M2, Inflation	5.68	7.30	7.95
FoS M2, Flight	19.30	40.50	58.57
FoS M3, Inflation	6.09	7.08	7.46
FoS M3, Flight	20.69	39.39	54.81

The balloon neck has three modes of failure - The first failure mode is the fracture of the neck, the second failure mode is shear of the neck at the load point, and the third failure mode is the neck slipping from the neck wrap, due to a heavy payload or the neck being inadequately secured. In-depth calculations of each failure mode can be found in Appendix 10.1 - Neck Strength Analysis.

Test Overview: The extra 2000 gram latex balloon was hung uninflated from the aerospace building high bay ceiling. The balloon top was tied to a loop secured to the ceiling and the balloon neck was tied off in the same procedure used for the final flight from the carabiner. The carabiner was loaded incrementally up to 90 pounds, 15 pounds more than expected at the maximum wind loading case on the neck. This maximum case is an upwards wind creating additional lift from drag.

Measurements: The neck was visually inspected for damage and creep was measured. The neck was observed to be fully intact after 20 hours of loading. Significant creep was observed to be nearly one foot. This was discovered to be due to slippage of the neck after it was tied off and was stopped by the several loops of rubber bands used to help secure the balloon. This slippage was deemed acceptable because its effective increase in neck length did not endanger the structural integrity of the final test.

Verification: The demonstration of the tied off neck to withstand constant loading 23% above the maximum gust expected shows that the neck will retain its integrity during the highest loadings allowed within the design.

Validation: A loading of 90 lbs translates to 400 N of force on the neck of the balloon. This loading is 23% higher than the highest loading on the model, which is 308 N, assuming 40 mph winds blowing straight up. The factors of safety for the 308 N loading calculation were all above 7, indicating a low likelihood of failure. The observed creep from the test indicates that with an even higher loading of the neck comparable to 40 mph winds, the system will not fail. Requirements DR1.4 and FR2 are then satisfied, as the balloon will be able to be secured to the ground and also be airborne for 20 hours.

5.6. Power Test

> FR3 - The system shall be provided enough power to sustain a 1 day flight.

> DR3.1 - The system shall not draw more power than the battery can provide.

Model: The power for this project is supplied by a Trojan 27TMX battery, a 12V deep cycle flooded lead-acid battery capable of providing 105 Ah for the duration of a 20-hour flight. The battery is charged by a 300W monocrystalline solar panel, which connects to the battery through a 30A charge controller. To satisfy DR 3.1, the system altogether shall not draw more power than what the battery is capable of providing. The capacity of a battery can be found by simply multiplying the battery's amp-hour capability with its voltage rating. Thus, the Trojan 27TMX battery can provide 1260 Whr, which equates to 63 Watts over a 20 hour testing period. Thus, all components in the system are limited by this 63 Watt cap. Based on the datasheets of all components, it is expected that the power draw will not exceed 25W. To validate this, a model was developed that estimates the battery's capacity over time. Within this model, every component of the system that draws power is accounted for, as well as a charging cycle approximating power generated by the solar panel. It should be noted that the solar panel will not be placed at an angle, but will instead be laid horizontally on the ground. Doing this allows for an approximation to be made that the angle of incidence is equivalent to the zenith angle, which can be easily found for each hour of a specific day in March. The National Renewable Energy Laboratory (NREL) has developed a model that estimates insolation and direct beam from the sun on a horizontal surface for a clear day, called the Bird Clear Sky Model. Using this model, the direct beam data for a day in March was extracted and used to predict the amount of power the solar panels will be able to generate over a 20 hour testing period. The figure below shows the amount of power capable of being generated by the solar panels based on the direct beam data from the NREL Bird model. It should be noted that the power generated by the solar panels has been multiplied by 0.2 to account for the typical 20% efficiency of solar panels.

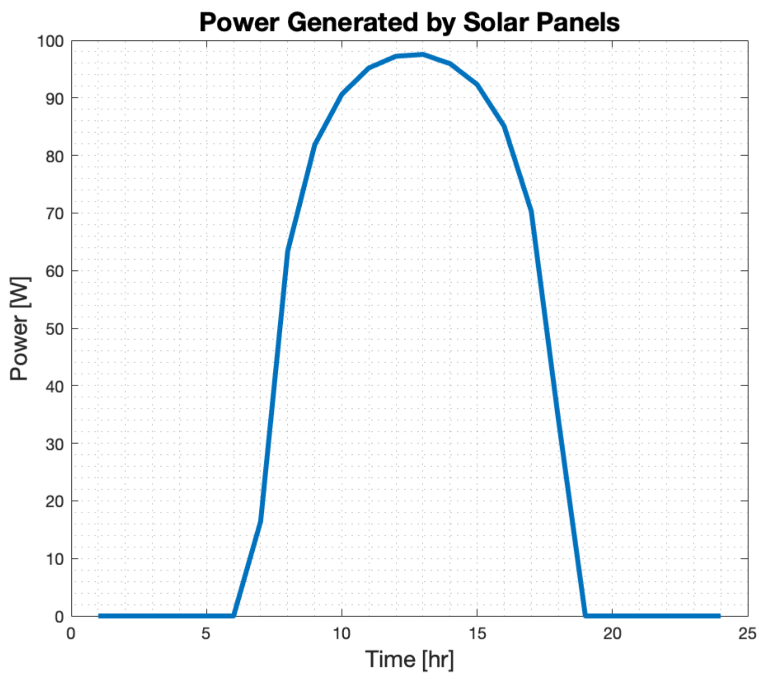


Figure 28: Estimated Generated Power vs. Time

Fig. 28 shows that the solar panels are capable of providing a total of 920 Watts for a 20 hour testing period, if needed. This is sufficient to charge the Trojan 27TMX battery to 73% from empty.

To meet DR 3.1, the operational and maximum power ratings for each component were collected from their respective datasheets. From this information, it is expected that the power draw by all components will be approximately 13.6W. The line losses associated with the power cable running up to the flight vehicle must also be incorporated into this model. The balloon will ideally fly at an altitude of 118 feet, with tethers at a 45 degree angle. This equates to a 167 foot tether length. A 16 gauge annealed copper wire has a resistivity of 5.64e^{-8} Ohm-feet and a cross sectional area of 1.41e^{-5} square feet. Using this information, the resistance of this wire can be calculated as follows.

$$R = \frac{\rho L}{A} \tag{4}$$

The power line loss can then be calculated by multiplying this resistance by the total current draw squared. For the estimated current drawn by the flight components, the line loss is expected to be around 1.58W. This makes the total power draw around 15.1W, much less than the battery max capability. Incorporating the operational power draws and line loss into the power model produces the following plot.

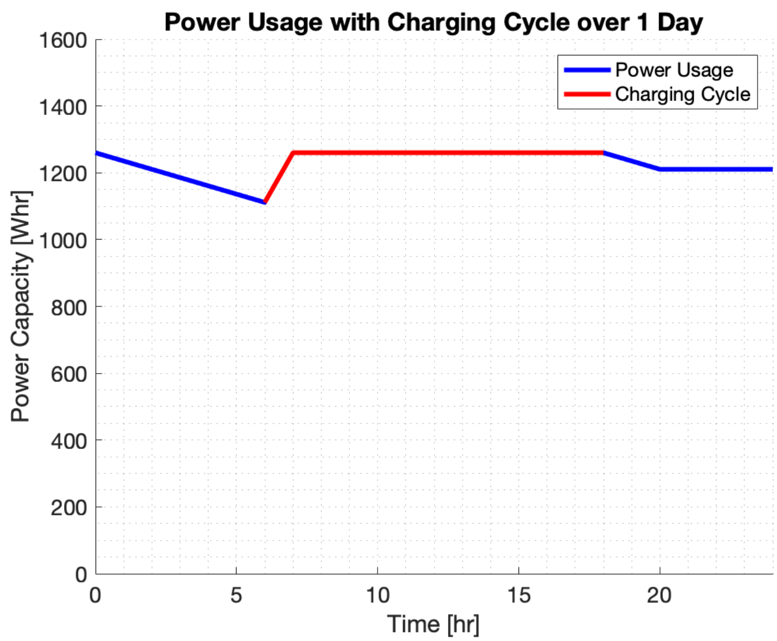


Figure 29: Battery Capacity vs. Time

As seen in Fig. 29, the solar panels, even at 20%, are expected to have no issue charging the battery back to full capacity with the Bird model data. This figure also accounts for a four hour downtime where all components are turned off and no power is being drawn.

Test Overview: The testing of the power supply system consisted of three main tests: the battery discharge test, the solar charging test, and the full system power test. The battery discharge test involved connecting the Trojan 27TMX deep cycle battery to a Keithley SourceMeter 2460. The SourceMeter was configured to draw 3A of constant current until either 20 hours had elapsed or the battery wasn't discharged. The solar charging test involved connecting the drained battery to the solar panels and allowing the battery to return to full capacity. Lastly, the full system power test, which did not end up being completed, would have involved integrating all electronic components into the instrument suite and ground station, connecting power, and allowing it to run for the full 20 hours.

Measurements: The measurements acquired from the battery discharge test were voltage readings versus time, which allowed for a discharge curve to be generated. The main measurement from the solar charging test was in the form of how many hours it took for the battery to reach full capacity from empty. Lastly, the measurements from the full system power test would have been binary: either all components operated properly for the duration of the flight, or at least one of them did not.

Verification: The results from the battery discharge test indicate that the battery is fully capable of powering the full system for the duration of the 20 hour flight, without any assistance from the solar panels. The results from the solar charging test indicate that the solar panels are capable of charging the battery from empty within the span of 5 hours. Both of these test results allow the team to conclude that between the solar panels and battery, there will always be sufficient power supplied to the system for the duration of the final flight. The full system power test, if it had been conducted, would have provided further confirmation of this.

Validation: The conclusion from these tests validate the FR 3 by proving that the power production system is capable of providing enough power to sustain the system for the duration of a 1 day flight. DR 3.1 would have been validated by the full system power test, the results of which would have proved that the power draw of all components was less than what the battery could provide.

5.7. Thermal and Condensation Test

DR4.4 - The imaging system shall have the capability to image for 80% of any testing period during operational conditions.

Model: The goal of the condensation model is to ensure through thermal analysis that condensation will not form on the imaging surfaces during flight. The imaging surfaces are the camera lens and the inner and outer polycarbonate faces. Two models were used for this. The first model, called the Bögel model, is based on the Arden Buck equations developed in 1996. These equations find the dew point for water as a function of temperature, relative humidity, and a variety of empirical constants. The results of this model are shown in the plot below, which demonstrates the required temperature difference between any surface and the ambient conditions required to prevent condensation. This plot shows the temperature raise as a function of the temperature/time of day for Boulder, Colorado at different relative humidities.

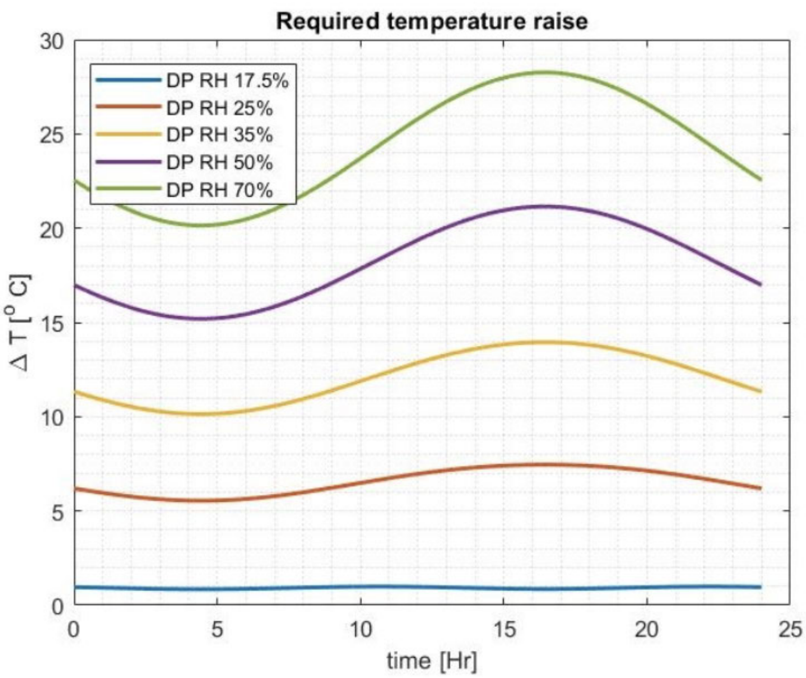


Figure 30: Bögel Model

The second model involved allows the group to verify that all thermodynamics inside of the instrument suite were properly modeled. This model relates the temperature inside the instrument suite to the temperatures of the outside surface of the polycarbonate and the ambient air. The model is a four node one-dimensional heat transfer model, and assumes convection on the inside and outside of the instrument suite, with conduction through the polycarbonate sheet. The temperature gradient through the polycarbonate is assumed to be linear. The following diagram shows a visual representation of the model. Again, the goal here is to verify thermodynamic calculations with experimental data.

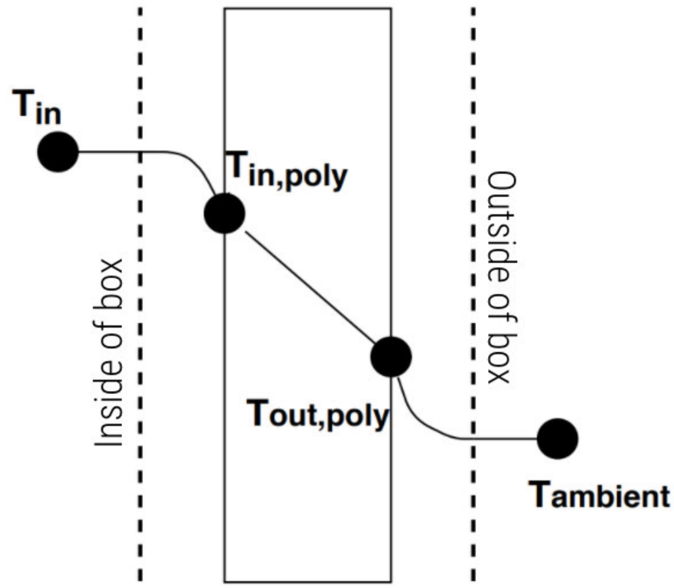


Figure 31: 1-D Thermodynamics Model Through Polycarbonate Sheet

Test Overview: Three tests were performed to determine if condensation was expected to occur during the final flight. These tests were conducted in the ASTRA thermal chamber. All electronic components as well as the polycarbonate imaging surface were integrated into the instrument suite before being installed into the thermal chamber. Also installed in the thermal chamber were two ASTRA-provided thermistors, an ASTRA-provided humidity sensor, and two thermocouples acquired from the Electronics Shop. The battery was placed outside of the thermal chamber, and a power cable was fed to the instrument suite. One of the three thermal tests was conducted with ambient humidity. For the other two tests, humidity was pumped into the thermal chamber using a COTS humidifier and tubing. The first test was conducted at -12C and ambient humidity, approximately 10%. For the second test, the thermal chamber was again set to -12 C, but the ambient humidity was increased to 50%. The third and final test was conducted at 21 C, with an ambient humidity fluctuating between 40% and 80%. For all three tests, a visual inspection of the imaging surface for condensation was conducted every 10 minutes. The test would be stopped if condensation was observed. However, no condensation was observed on the imaging surface over the duration of these three tests.

Measurements: The measurements acquired through these three tests were in the form of four temperature readings, two from the thermistors and two from the thermocouples, as well as a humidity reading. There was an approximately three degree C temperature difference between the thermistor and thermocouple readings, likely due to a discrepancy in accuracy between the sensors. The binary condensation or no condensation observation was also recorded.

Verification: The Bögel model led the team to believe that condensation would be expected to occur on the imaging surface if the difference between the temperature of the outside of the polycarbonate and the ambient temperature was less than 20 degrees C, given an ambient humidity of 50%. Throughout these tests, at an ambient humidity of approximately 50% or higher, the temperature difference between the outside of the polycarbonate and the ambient temperature was never equal to or greater than 20 degrees C. Therefore, condensation was expected to occur. However, none was observed. This led the team to question the accuracy of the Bögel model, and after some research, it was found that some assumptions made in the Bögel model were outdated. Thus, the team turned to the 1D thermal model of the polycarbonate sheet in order to determine if the experimental results from the thermal tests were reasonable. By using the measured temperatures of the inside of the the box and the ambient air, the temperature of the outside of the polycarbonate could be estimated. The resulting values matched those that were experimentally found, thus confirming that the experimental data collected was accurate. From here, the team concluded that the Bögel model was not a reliable estimation of condensation occurrence, and that the team could expect to not experience condensation during the final flight.

Validation: This conclusion satisfies DR 4.4 in that by not expecting to experience condensation, the imaging system will be capable of operating properly for the duration of the flight.

5.8. Final Flight

FR1 - FR11

Model: All previous models and calculations will be demonstrated again by the final full-scale flight by integrating all subsystems. From the lift model and test, the balloon is expected to provide the required lift to maintain the design altitude for the entire flight duration. From the camera pointing model and test, the NIR camera is expected to produce images including the minimum required 300 square feet as per design requirements. From the power model and test, the battery and solar panels are expected to provide the required power for all electronic components throughout the duration of the flight. From the thermal model and condensation test, no condensation is expected to occur on any imaging surfaces throughout the duration of the flight.

Test Overview: All equipment and tools are gathered in the Aerospace building and compared to the materials checklist. All equipment is transported to the CU South Boulder test site. The locations for mooring stations are measured out and mooring stations placed, staked, and sand bagged. The tethers are unwound to the center and the airborne structure is attached. The helium tanks and fixtures are brought to the airborne structure. The balloon tarp and balloon are laid out and inspected. The balloon is attached to the fittings and filled to produce the required lift. The tether spools are unwound until the instrument suite has ascended to operational altitude and verified with the laser range finder. Soil moisture samples are taken, bagged, and masses. Soil moisture probes are placed in the minimum viewable area and data recording initiated. The solar panels are connected to the battery, and all electronic components are connected to power. The ground processor is used to initiate imaging and data recording. The test is monitored for the flight duration. Finally the balloon is winched in, deflated, and all materials are returned to the aerospace building for post processing.

Measurements: The key measurements recorded are NIR images and atmospheric data. The images will be post processed and aligned so no issues are expected. The atmospheric data includes magnetometer readings, camera temperature, and ambient pressure. Wind speed, GPS, and soil moisture resistance values will be recorded on the ground. Key concerns include pressure data fluctuations which are mitigated by the large increase required to activate the ARRD and GPS data accuracy which will be analyzed by the customer.

Verification: The final flight will show by demonstration the success of the flight vehicle, structural components, electronics, camera imaging, soil moisture data collection, software, and power systems.

Validation: The final flight will validate the project against functional requirements FR1 through FR11.

5.9. Automatic Rapid Deflation Device

DR11.1.2 - The flight vehicle shall have a rapid deflation device onboard in the event of an emergency.

Model: The melting point of latex is 180 degrees C. NiCr80 wire at 16ga requires 8.31 amps to reach 316 degrees C. 16 gauge is workable and holds its shape. 316 degrees gives a large margin above the latex melting point. Using Ohm's law and incorporating a regulating resistor, a length of 0.795 feet in series with the regulating MOSFET and 0.2 Ohm resistor will produce the desired temperature from a 3.7 volt single cell LiPo battery

Test Overview: After the ARRD would have been assembled, the temperature test procedure would be to inflate one of the 200 gram latex balloons, wrap the ARRD NiCr80 wire around the neck, and power the wire. The balloon would be expected to deflate within three minutes to comply with the vague wording "rapidly deflate" in the FAA requirements on tethered balloons. The second test would be to simulate an increase in altitude by bringing the ARDD assembly from the first floor to the fourth floor of the aerospace building and ensure the wire has begun to heat up from a decrease in pressure.

Measurements: Aside from visual inspection, the key measurement is timing the deflation of the balloon. This may vary significantly and as long as the time can be justified as “rapid” the test is successful.

Verification: Inspecting that the ARRD initiates heating the wire from an altitude increase of four stories, and that the wire melts a large enough hole to allow rapid deflation, the ARDD test verifies it has met the testing requirements.

Validation: By triggering to close the circuit once a predetermined pressure differential is experienced, and by melting a sufficiently large hole in the latex balloon, the ARDD system proves that it is capable of acting as a rapid deflation device, and satisfies DR 11.1.2.

6. Risk Assessment and Mitigation

Alexis Wall

During the design stage of this project, six key risks were identified that, without mitigation, could potentially cause issues during the build and test phase. These six risks as well as their likelihood of occurring and severity of consequence are listed in the following table. Risk IDs 1 through 6 are used throughout this section for ease of tracking.

Table 24: Risk Identification and Descriptions

ID	Risk	Likelihood	Severity	Details
1	Condensation Ruins Images	High	Moderate	In high relative humidity, a temperature gradient between the inner surface and outer surface of the instrument housing can cause condensation to build up, distorting images collected by the camera during an outdoor test.
2	Weather Damage	Ext. High	Severe	Sensitive electronics and electrical connections are susceptible to water damage and the ground structure can be strained or compromised in high wind conditions.
3	Test Schedule Slips	High	Major	Multiple 20-24 hour tests are required prior to the final day in the life test. If the test schedule slips due to inclement weather or other concerns, the team may run out of time to properly test before final deployment of the system.
4	Mass too Large	Medium	Major	The weather balloon will be carrying a larger mass than most weather balloons, as it must compensate for the mass of mooring tethers as well as the instrument suite. A higher mass leads to a smaller net force upwards by the lifting vehicle, which can lead to a system more heavily swayed by wind.
5	Team Member Injury	Low	Severe	This project requires the team to metal-work, wood-work, and work with electronics that deal with high current. If a team member is injured, they will be unable to properly support the mission.
6	Budget does not Allow all Testing	High	Major	Each full scale test requires a new weather balloon and multiple tanks of helium. This makes the cost of one flight more than $700. If multiple tests are required prior to the final data collection period, the budget may not support full testing.

The likelihood and severity assignments for each risk were used to formulate the following risk matrix, containing the aforementioned risk IDs. The color code goes from green to red, indicating how fervently each risk needed mitigation. A risk in the green zone should be monitored but did not necessitate change. Slightly more severe is a yellow risk that needed aggressive monitoring and warranted caution while handling related project elements. An orange risk required small changes to be implemented and a red risk necessitated large scale changes in order to avoid jeopardizing the system’s success.

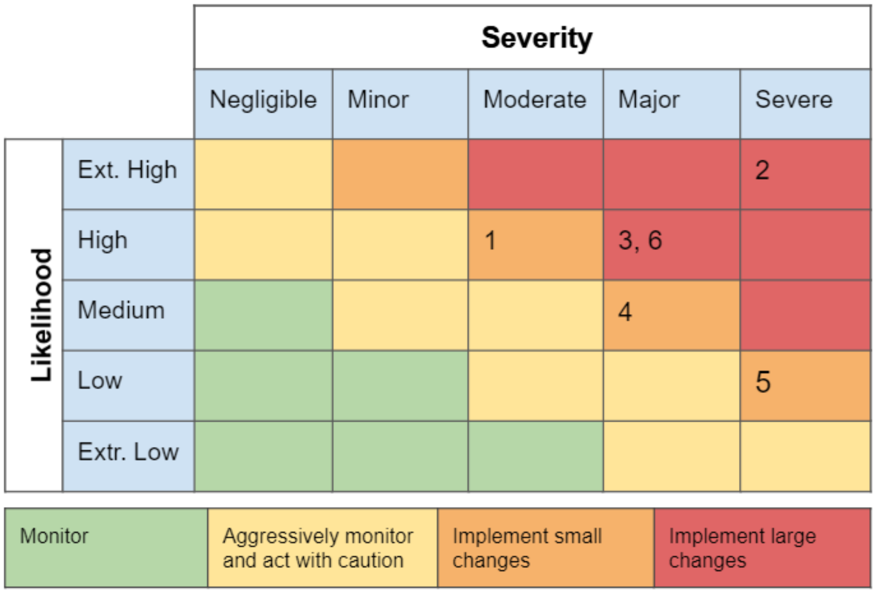


Figure 32: Pre-Mitigation Risk Matrix

Risks are only shown in the above matrix if they are considered severe and likely enough to necessitate a change in design or policy. Since identification of these six risks, mitigation strategies have been implemented in design and implemented as applicable in the build and test phase. The following mitigation strategies were implemented and a discussion follows to indicate which risks were realized in build/test:

Risk 1 Mitigation: Condensation Ruins Images

- Initial planned mitigation strategies included applying hydrophobic coating to imaging surface of instrument suite, adding a heater to the instrument suite, and not testing on days where relative humidity is greater than 50%.
- Exercising caution before adding a heater and hydrophobic coating, the team tested in conditions up to 80% humidity and did not observe condensation. The team decided a heater and hydrophobic coating were not necessary and the 50% maximum humidity testing condition was considered adequate mitigation.
- Post-mitigation likelihood: Ext. Low
- Post-mitigation severity: Minor

Risk 2 Mitigation: Weather Damage

- Initial planned strategies include avoiding testing when inclement weather is expected (high winds/rain), making the instrument suite water resistant, and reinforcing the ground structures with additional mooring weight.
- All of these strategies were implemented. The instrument suite did not incur damage during any form of testing.
- Post-mitigation likelihood: Low
- Post-mitigation severity: Moderate

Risk 3 Mitigation: Test Schedule Slips

- Initial planned strategies included developing robust test plans that could be executed indoors if possible and planning backup days for testing in case of inclement weather.
- These strategies were used and the testing schedule for any given subsystem never slipped more than a week. Overall, the mitigation strategies were successful. They were useful for executing some soil moisture imaging tests as well as the diffusion test.
- Post-mitigation likelihood: Low
- Post-mitigation severity: Minor

Risk 4 Mitigation: Mass too Large

- Initial planned strategies included decreasing the designed altitude of the instrument suite from 150 to 118 feet to decrease tether mass significantly and reinforcing the connection of the airborne structure to the neck of the balloon to decrease the likelihood of neck tear.

- These strategies were put in place and the design changes were useful in the neck strength test. The final flight was expected to have proven the system could maintain required lift.
- Post-mitigation likelihood: Low
- Post-mitigation severity: Minor

Risk 5 Mitigation: Team Member Injury

- Planned mitigation strategies included clearing all test and build procedures for safety before implementation and ensuring relevant team members have attended safety courses and trainings.
- This strategy was implemented. Relevant staff was present for all tests where safety was a concern and all procedures were cleared. Subsequently, no team member was injured in the build or test phase.
- Post-mitigation likelihood: Ext. Low
- Post-mitigation severity: Major

Risk 6 Mitigation: Budget does not Allow for all Testing

- Planned mitigation strategies included limiting the use of helium wherever possible by implementing scaled down model tests and designing tests to verify requirements without having to fly whenever possible. The team also spoke to the customer about acquiring more funds in case the final test was unsuccessful and needed to be redone.
- These strategies were implemented and some scaled tests were conducted (neck strength and diffusion test). Unless the first day in the life test failed, the team was expected to finish testing without exceeding budgetary constraints.
- Post-mitigation likelihood: Low
- Post-mitigation severity: Moderate

After employing these mitigation strategies, the post-risk mitigation matrix is shown below.

		Severity				
		Negligible	Minor	Moderate	Major	Severe
Likelihood	Ext. High					
	High					
	Medium					
	Low		3, 4	2, 6		
	Extr. Low		1		5	

Monitor	Aggressively monitor and act with caution	Implement small changes	Implement large changes

Figure 33: Post-Mitigation Risk Matrix

All of the risks moved from the orange and red zones to the green and yellow zones which indicates that the major risks had effective mitigation strategies in place.

Because of effective risk mitigation and testing practices, the team had not yet realized any significant issues during testing that could not be easily solved. Had the heater been required to prevent condensation, the power system would've required a redesign to support the heater's power draw. This was the biggest fear realized when testing but thermal chamber humid tests showed the heater to be unnecessary to image properly.

7. Project Planning

Riley Perez, Eric Vanderwolf

7.1. Organizational Chart

Fig. 34 shows the organizational chart for Team WIRMS. Each member had their own respective technical lead position for a specific component of the project and reported to the systems engineer and project manager. Team members concentrated on their lead area but contributed to other subsystem's work when applicable. Regular updates on progress and areas of concern were given to ensure fluid communication and timely completion of subsystem work.

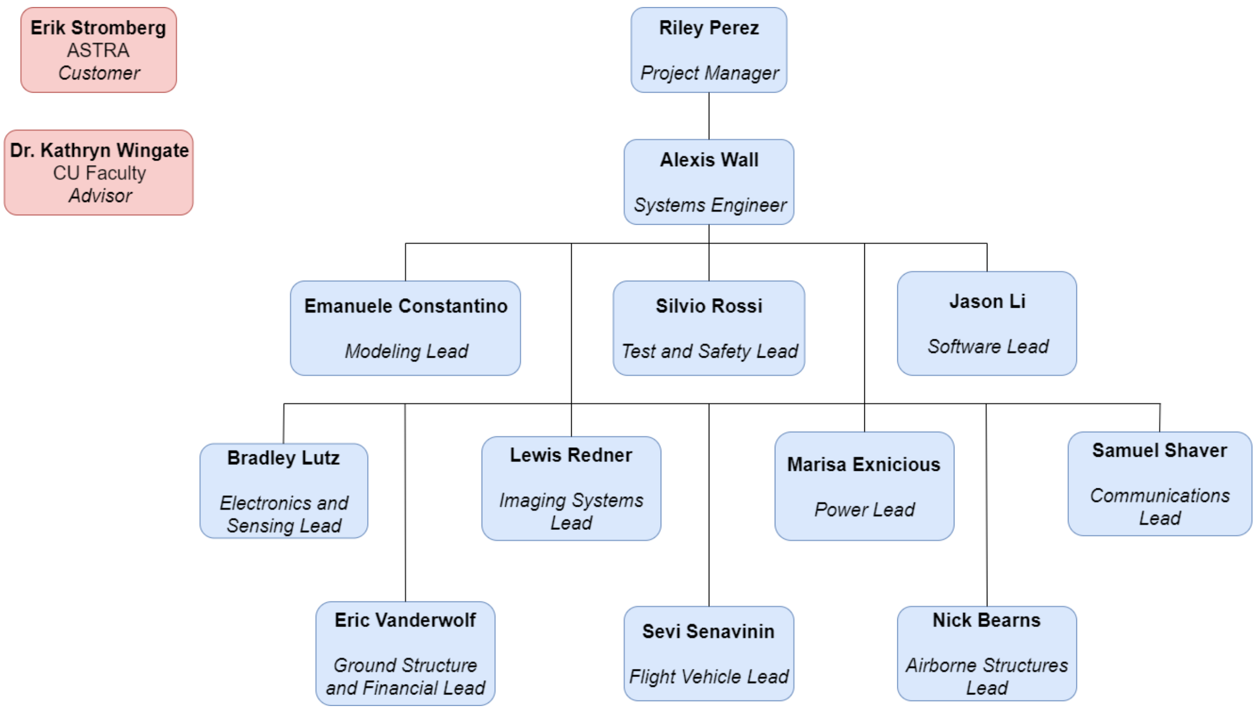


Figure 34: Team WIRMS Organizational Chart

7.2. Work Breakdown Structures

The work breakdown structure can be seen below in Fig. 35. This figure shows the work that was completed across both fall and spring semesters and what was left unfinished due to the COVID-19 shutdown. The first column shows the deliverables for this project. The management tasks have been completed by the project manager, systems engineer, and financial lead. The flight vehicle, airborne/ground structures, electronics/power, and data processing columns show the work required for these subsystems that were completed by their respective leads. Safety/testing procedures and scheduling were developed by the safety lead. The items seen in this chart showcase the main tasks that were required for successful completion of this project.

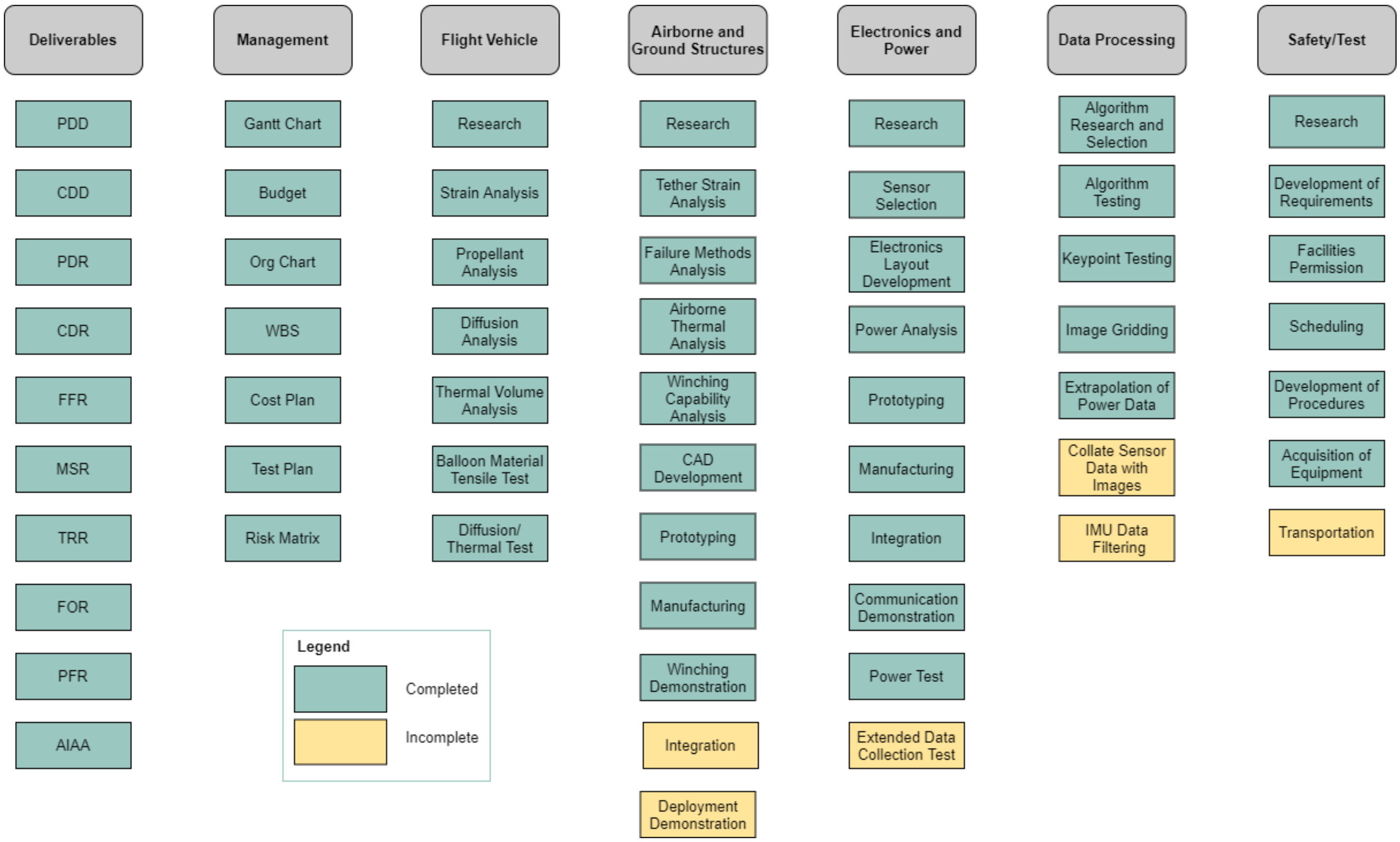


Figure 35: Team WIRMS Work Breakdown Structure

7.3. Work Plan

The work plan can be seen below in Fig. 36 in the form of a Gantt chart. The critical path for the progression of this project is signified by the red arrows, which highlight the importance of each main phase.The progression has been split into three main phases: manufacturing, assembly, and testing. The manufacturing phase involved the purchasing of COTS components, as well as the fabrication of in house components. The assembly phase included assembling the ground and airborne structures, as well as the power and electronics systems. Once assembly was completed, component level testing was conducted and nearly completed, as the pointing test was the only component level test that was not conducted. Completion of these component level tests lead to the initial and final field testing that was going to occur in mid March to early April. The solid filled portions represent tasks that were completed, where tasks with unshaded portions show the margin that was allotted. This chart shows that the only tasks that were not fully completed were software development, the pointing test, as well as the initial and final field testing. Larger margin was given to the software development as well as the initial and final field testing, as it was anticipated that issues would arise during integration that needed to be properly accounted for in the schedule. Furthermore, the field tests relied heavily on good weather and supervision from the flight director Dan Hesselius and Matt Rhode.

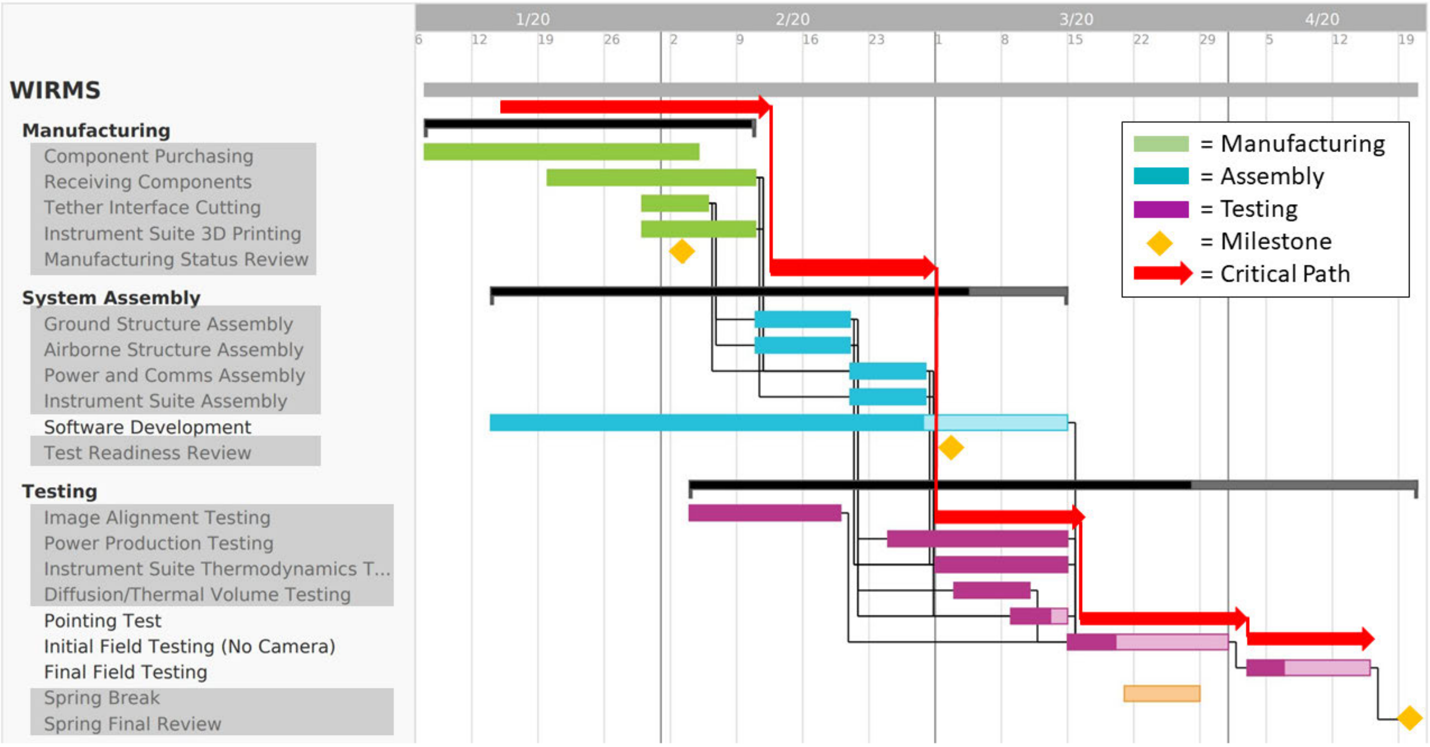


Figure 36: Team WIRMS Gantt Chart

7.4. Cost Plan

The WIRMS financial budget is shown in Figure 37 below. The major items that were purchased include the helium for the final flights and testing ($1187.88), the solar panels for the ground systems ($315.00), and the weather balloons for flights and testing ($740). The full budget was then compiled by subsystem to create a bar chart of predicted vs actual expenditures. These expenses can be seen in Figure 38, shown below. The team's predicted net cost was $4094 with a remaining margin of 18%. The actual cost came to $4449 with a remaining margin of 11%. This discrepancy between predicted and actual expenditures resulted from miscellaneous testing items that were not previously accounted for, shipping costs, as well as an increase in the size of the instrument suite 3d printed box. There was some concern about additional flights being required in the event of failure of the initial or final field test given the high cost of balloons and helium. However, this risk was discussed with the customer, ASTRA, who confirmed that they would be willing to purchase additional helium tanks in the event of flight failure.

SubSystems	Items	Cost/Item	Number of Units	Total Cost
Ground Structure				
	Weatherproof box	$ 127.00	1	$ 127.00
	Worm Hand Winch	$ 96.61	3	$ 289.83
	Aluminum plates	$ 61.30	3	$ 183.90
	Bolts/Nuts	$ 10.36	1	$ 10.36
	Stakes	$ 7.00	6	$ 42.00
	Drill Attachments	$ 17.85	1	$ 17.85
	50 lbf bag of sand	$ 4.20	6	$ 25.20
Airborne Structures				
	Polycarbonate	$ 4.56	1	$ 4.56
	ABS	$ 117.88	1	$ 117.88
	fasteners	$ 38.22	1	$ 38.22
	1000 ft kevlar rope	$ 105.00	1	$ 105.00
	Styrofoam	$ 16.99	1	$ 16.99
	Velcro	$ 12.89	1	$ 12.89
	ASI MOUNT	$ 17.48	1	$ 17.48
	Caulk	$ 6.98	1	$ 6.98
	White enamel spray paint	$ 3.98	1	$ 3.98
	Aluminum	$ 141.36	1	$ 141.36
Electronics				
	USB Cord	$ 9.91	1	$ 9.91
	Anemometer	$ 60.91	1	$ 60.91
	Raspberry Pi	$ 60.00	2	$ 120.00
	Atmospheric Sensor	$ 23.57	2	$ 47.14
	Gyro	$ 15.00	1	$ 15.00
	Heat Shrink	$ 4.00	1	$ 4.00
	1 TB hard drive	$ 11.49	1	$ 11.49
	ADC	$ 3.75	1	$ 3.75
	Deep cycle battery	$ 174.00	1	$ 174.00
	Solar Panel kit	$ 315.00	1	$ 315.00
	Raw wire (16 AWG)	$ 63.75	1	$ 63.75
	5V Buck converter	$ 9.95	2	$ 19.90
	25 Ohm resistor	$ 8.32	1	$ 8.32
	Fuse	$ 2.29	4	$ 9.16
	Fuse Holder	$ 0.25	4	$ 1.00
	9V Buck converter	$ 4.95	2	$ 9.90
	GPS-Air	$ 40.00	1	$ 40.00
	19418 Receptacle w/ CPA	$ 3.29	1	$ 3.29
	19429 Panel Mount w/ Gasket thru hole	$ 11.26	1	$ 11.26
	Female crimp terminal	$ 0.18	10	$ 1.80
	LCD	$ 19.95	1	$ 19.95
	GPS antenna	$ 25.20	1	$ 25.20
	Micro USB	$ 0.95	3	$ 2.85
	Male crimp terminal	$ 0.19	10	$ 1.90
Flight Vehicle				
	Flight Balloon	$ 250.00	1	$ 250.00
	Helium	$ 168.64	3	$ 505.92
	Ring	$ 4.95	1	$ 4.95
	Carabiner	$ 8.95	1	$ 8.95
	Rubber Bands	$ 9.00	1	$ 9.00
	Hose	$ 16.91	1	$ 16.91
	quick connects	$ 8.10	1	$ 8.10
	PVC	$ 15.88	1	$ 15.88
	CGA Adapter	$ 17.00	2	$ 34.00
Safety and Testing				
	Diffusion balloon	$ 30.00	1	$ 30.00
	Helium	$ 170.49	4	$ 681.96
	Neck Balloon	$ 230.00	2	$ 460.00
	Lipo	$ 20.00	1	$ 20.00
	MOSFET	$ 0.85	2	$ 1.70
	Pressure Sensor	$ 13.95	1	$ 13.95
	Nichrome Wire	$ 11.00	1	$ 11.00
	Soil Moisture sensor	$ 5.95	4	$ 23.80
	9V Battery (6pack)	$ 15.30	1	$ 15.30
	Arduino Nano	$ 25.00	1	$ 25.00
	FAA LED	$ 47.00	1	$ 47.00
	Condensation Hose	$ 8.28	1	$ 8.28
	Tape for tensil testing	$ 9.31	1	$ 9.31
	Teensy 4.0	$ 21.60	5	$ 108.00
Total Budget				$5,000.00
Total Sales Cost				-$4,449.97
Net Budget				$550.03

Figure 37: Team WIRMS Full Budget

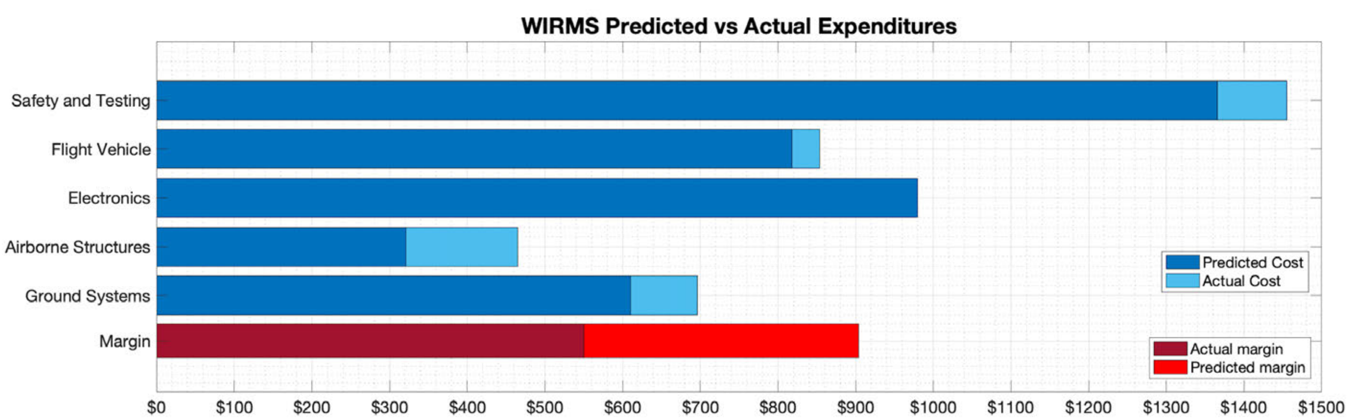


Figure 38: WIRMS Budget by Subsystem

7.5. Test Plan

Planning the logistics for tests was certainly an important aspect of the spring semester. Smaller subsystem tests were handled by each respective subsystem and did not require extensive planning or equipment. The four main component level tests that have been discussed (thermodynamics/condensation, pointing, power, and diffusion) required more planning as these involved multiple components of the project. These tests involved coordinating lab space such as the high bay, electronics room, and ASTRA's thermal chamber. Test lead Silvio Rossi and project manager Riley Perez frequently communicated with faculty members and ASTRA to coordinate scheduling for use of these various facilities well ahead of the scheduled test time given by the Gantt chart. Frequent and early communication resulted in little to no scheduling conflicts as all tests were completed during their scheduled times. The two field flights that were planned were also well coordinated with CU flight director Dan Hesselius and PAB member Matt Rhode. A detailed flight procedure was given to and approved by both of these faculty members well ahead of the planned flight period. Dan Hesselius requested 24 hour notice before any flights, and this request would have been followed had the team been able to fly prior to the shutdown.

Overall, test planning was successful. Frequent communication between the project manager and test lead, as well as the various subsystems, allowed smooth scheduling of the various component level tests that were required. Planning well ahead with faculty members allowed enough time for avoidance of scheduling conflicts.

8. Lessons Learned

Riley Perez

Throughout the completion of the WIRMS project there have been many lessons learned. Three key lessons are discussed below.

During the fall semester, setting the scope of the project through levels of success and requirements is crucial to the success of the project later down the road. It is very important to set realistic goals and discuss with the customer to make sure they are on board with the team's goals and expectations. Initially, ASTRA pitched the idea of a month long flight for collecting data. This was certainly out of scope for this course, so initially the team negotiated the flight time down to a week, which was assumed to be reasonable. However, after discussing with members of the PAB, even this was not deemed feasible, so ultimately the flight was reduced to a 24 hour period. This was a substantial decrease from the customer's initial request; however, they were very reasonable about accepting the scope of the course and agreed on the new flight time. Ultimately this new flight time set the team up for success later down the line by making design and test phase goals more achievable and would have made the final flight process much more reasonable had the team had the opportunity to conduct the final day-in-the-life test. Thus, negotiating with the customer to set a reasonable scope for the project is crucial for the team to be successful through the fall and spring semesters.

Since this project relied on NIR images as deliverables to the customer the imaging aspect of WIRMS was crucial for the project to be successful. During the design phase the team was advised to focus on the issue of condensation on the imaging surface as many past senior projects teams have critical condensation issues. Because of this, heavy emphasis was given to the thermodynamics of the instrument suite, both from an analysis and presentation standpoint. Both presentations in the fall semester talked about the camera and the model for condensation that was expected. The presentations in the spring similarly focused on test setup and test results for condensation. The test results for condensation discussed in section 5 showed that the condensation model that was used did not accurately reflect the results that were observed, due to factors such as material properties. This showed the importance of testing in humid environments to replicate the conditions expected during operation, to validate any condensation models that are used for optical oriented projects. Any teams that may have optics as a critical component to the project should focus on this issue specifically, as many PAB members will raise this as a concern.

Another critical component to this project was the weather balloon used as the flight vehicle. An issue that quickly arose during the design phase was the choice of helium or hydrogen for lifting gas. Hydrogen has a high lifting capacity and is relatively inexpensive but highly flammable and a safety risk to the team. When the team was considering the use of hydrogen the PAB requested a detailed procedure on how transportation of the gas, as well as filling and flight procedures were going to be handled. Helium is very expensive and does not have the same lifting capacity as hydrogen, but has a far lower chance of potentially explosive results. Ultimately, helium was chosen to greatly reduce the amount of risk posed to the team members and the project. However, this put a huge constraint on the budget. During the testing phase, a large team discussion and extensive planning was necessary to formulate appropriate tests that would reduce helium costs while providing enough data to move the project forward. This was accomplished by planning smaller scaled tests that did not require a fully inflated balloon, or changing test plans to remove the use of lifting gas completely (i.e. hanging the instrument suite from the high bay ceiling for the pointing test). It should be known for any balloon projects in the future that the choice of lifting gas is very important for determining how the project will function and that appropriate planning for testing must be in place to account for budgetary issues that may arise.

9. Individual Contributions

- Nicholas Bearns: CONOPS, CAD, renders, airbone structure design solution, airborne structure condensation analysis, airborne structure structural analysis, balloon tether, instrument suite manufacturing, balloon tether interface manufacturing, airborne structures integration
- Emanuele Costantino: Instrument suite dynamics modeling, environmental conditions modeling, camera modeling, camera trade study, camera attachment, AARD design/manufacturing, soil moisture sensor design/manufacturing
- Marisa Exnicious: Requirements development, project purpose, power system baseline design, rapid deflation device baseline design, power system manufacturing and integration, power model verification and validation
- Jason Li: Microcontroller trade study, data calibration trade study, image processing code, software systems code, software systems design, electronic sensors code, communication design
- Bradley Lutz: Sensor trade study and description, final baseline design description, detailed design section for sensors, manufacturing and integration for electronics, integration for flight vehicle
- Riley Perez: Project planning section, Gantt chart, organizational chart, lessons learned, test plan, scheduling and customer communication
- Lewis Redner: Microcontroller trade study, image processing baseline design, image processing code, data calibration trade study, software architecture design, software system code, software systems design
- Sevi Senavinin: Flight vehicle conceptual design & trade study, functional block diagram, diffusion analysis, balloon structural analysis, balloon inflation manufacturing and assembling, inflation procedure, diffusion and neck strength test
- Samuel Shaver: Project Purpose, communication method trade study, communication baseline design, electronics interconnect diagrams
- Silvio Rossi: Flight vehicle trade study, initial ARDD design and calculations, FAA research, test plan design, test execution, Verification and Validation
- Eric Vanderwolf: Power source trade study, ground structures baseline design, mooring station structural analysis, airborne structural analysis, team finances, ground structures section, transportation section, cost plan section
- Alexis Wall: Data calibration trade study & design, requirements development and upkeep, functional block diagram, project objectives section, soil moisture data collection design, risk section

10. Appendix

10.1. Neck Strength Analysis

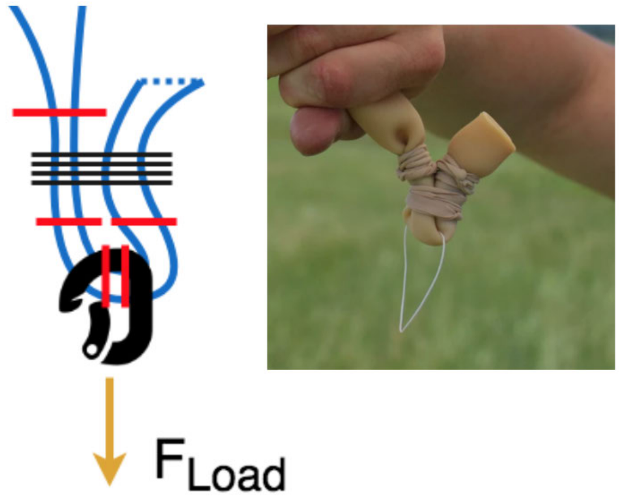


Figure 39: Neck tie-off description

Figure 39 shows the most simple, lightweight method used by weather balloon satellite researchers. For this application, a smooth carabiner or ring will be used to connect the load. In Figure 39, the red lines indicate the failure modes, and the black horizontal lines indicate the neck wrapping material.

The first failure mode is the fracture of the neck, represented by the red horizontal lines in Figure 39. This is occur if the neck elongates to a critical level. For the calculations, it was assumed that the neck would break in the region of smallest area, which is the single red horizontal line. Constant volume and constant strain rate of the neck was assumed. The normal stress was calculated and compared with the tensile strength of latex. Using σ_{TS} = 20.68 MPa for latex, and assuming the neck thickness calculated previously, the failing force of the neck can be found using the following equation.

$$F_{failM1} = \sigma_{TS} \cdot A_{neck} \tag{5}$$

The loading force on the neck can be separated into two phases - inflation and flight. During inflation of the balloon, the neck of the balloon is subject to the full force of lift, L_{actual}, due to the neck having to be hold down before the payload can be attached. During flight, the neck experiences the net lifting force, L_{net}, with the payload attached and staked down. The equation $FoS_{M1} = F_{failM1}/F_{load}$ is used to calculate the factor of safety.

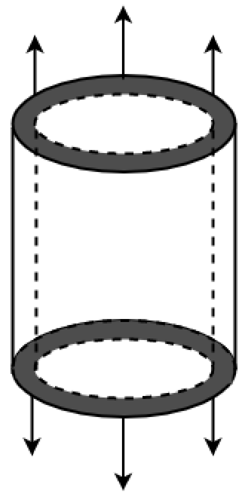


Figure 40: Method of failure 1

For the first method of failure, the factor of safety was calculated to be 7.05 to 10.95 during inflation, 15.50 to 80.50 during flight, and 8.60 to 19.25 during flight with 20 mph winds, depending on the propellant. The team can be assured that the neck will not fracture.

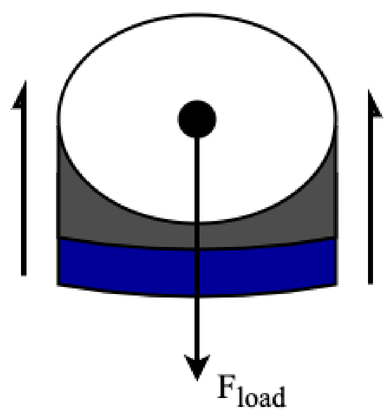


Figure 41: Method of failure 2

The second failure mode is shear of the neck at the load point. This could occur if the load is too heavy or if there is a sudden jerk at the load point. In Figure 39, this is represented by the vertical red lines. Using a Von Mises yield criterion assumption, which assumes the shear failure of latex is $0.577 \cdot \sigma_{TS}$, the failing shear strength was calculated to be 11.932 MPa. The area of the neck can be calculated using $A_{shear} = 2 \cdot t_{neck} \cdot d_s$, where d_s is the distance between the center of the carabiner/ring to the bottom of the shear thickness. d_s is assumed to be 5cm in this case. The shear strength during inflation and flight is calculated using $\tau_{failM2} = L_{load}/A_{shear}$. For the second failure mode, the factor of safety was calculated to be 5.12 to 7.95 during inflation, 11.30 to 58.57 during flight, and 6.26 to 13.98 during flight with 20 mph winds, depending on the propellant. The team can be assured that the neck will not shear.

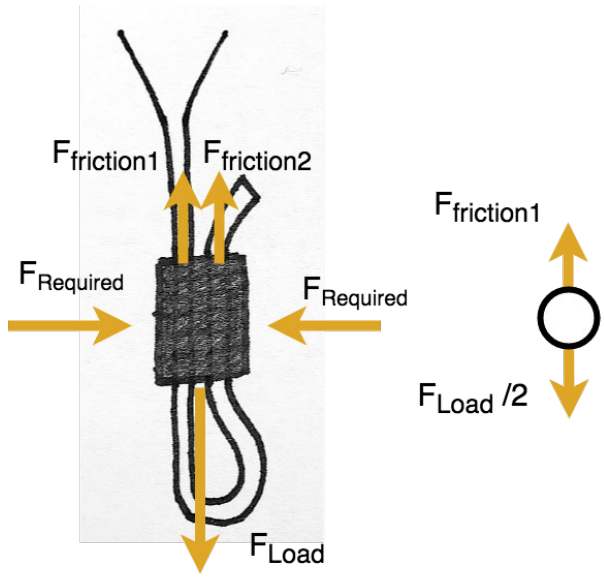


Figure 42: Method of failure 3

The third failure mode is the neck slipping from the neck wrap, due to a heavy payload or the neck being inadequately secured. The force of friction is defined as $F_{friction} = \mu \cdot F_{required}$, where μ is the coefficient of friction between rubber and rubber or rubber to metal, and $F_{required}$ is the force required to hold the two parts of the neck together. There are two choices to securing the two sides of the neck - using rubber bands to wrap both sides, or using a metal shaft collar to tighten both sides together. Separating each side of the neck to form its own free body diagram (Figure 42), the forces can be summed up and balanced. The coefficient of friction from rubber to metal is assumed to be 0.64 (Engineer's Edge), and from rubber to rubber is assumed to be 1.16 (Engineering Toolbox). Summarizing the equations, the force required is expressed as,

$$F_{required} = \frac{L_{load}}{(2 \cdot \mu)} \tag{6}$$

It was calculated that the force required to hold the two parts of the neck together was lower using rubber bands, but because rubber bands are unreliable, the following calculations use a shaft collar. The clamping force a shaft collar experiences is determined by the screw that is used to tighten the collar. Therefore, the first method of failure for a shaft collar is shear of the screw used to tighten the collar. Assuming a M6 screw for the shaft collar, which has a failing strength of 1 kN, the factor of safety can be calculated using the equation $FoS_{M3} = F_{screw,fail}/F_{required,shaftcollar}$. For the third failure mode, the factor of safety was calculated to be 5.49 to 7.46 during inflation, 5.49 to 54.81 during flight, and 6.71 to 13.11 during flight with 20 mph winds, depending on the propellant.

It should also be noted that the manufacturer has recommended that the balloon not be reused after one flight, due to degradation of the balloon material. Weather balloons are also designed to have a flight time of 1-4 hours and explode high in the atmosphere. However, through the analysis, the team can be assured that Functional Requirement 2 - "The flight vehicle shall be capable of operating in the air for 1 day" can be achieved.

10.2. Trade Studies - Pros and Cons

Flight Vehicle

Weather Balloon

One of the most common flight vehicles used in today's weather industry is the weather balloon. These are typically made of latex or neoprene and usually filled with helium. Weather balloons in industry, however, are not tethered. Instead, they rise to their bursting altitude, where the balloon nearly quadruples in diameter, and the payload falls back to Earth with an attached parachute. One drawback to using these balloons is that they have a typical endurance of

2 hours[2], and there is little to no data available on reusability or long endurance at a static altitude. Another disadvantage to using a weather balloon is their tendency to leak via diffusion, leading to losses in altitude. A significant leak may result in the balloon having to be retracted and refilled during the testing period. However, these balloons come with a low price tag relative to all other vehicles traded, and can typically endure temperatures as low as -95C and winds approaching 200 mph. Weather balloons are available at different weights, which correspond to different inflated diameters with a greater weigh corresponding to a greater inflated diameter. This allows for flexibility in finding the appropriate lifting capability to maintain altitude while avoiding overstraining the support structures. 3000 gram latex weather balloons, the largest available for purchase, costs around $500. Filling the balloon will require a minimum of two team members, one to operate the hose and one to hold the inflating balloon.

Table 25: Weather Balloons Pros and Cons

Pros	**Cons**
Low cost	Diffusion uncertainty
Availability	Reusability and endurance
Does not require human presence at all times	Weather susceptibility

Aerostat Balloon

Similar to a weather balloon, an aerostat is any large tethered balloon system. However, unlike the weather balloon, they are designed for long duration use. Usually taking the form of blimps, aerostats have been employed by several military organizations for surveillance. Aerostats usually have several tether attachment points which would provide more options for integration to other subsystem components. Aerostats typically have the endurance capabilities required for the scope of this project, however, their monetary costs and required development time may be prohibitive for the scale required for this project. Lightweight aerostats can typically hold a payload of 12 kg and can stay aloft for days while maintaining altitude. However, they are priced at around $10,000 dollars.

Table 26: Aerostat Balloon Pros and Cons

Pros	**Cons**
Flight endurance	High cost
Reusability	
Does not require human presence at all times	

UAV Multirotor

Multirotor endurance has been progressing and many companies boast extended flight times. The benefits of a multirotor system would primarily be heritage and integration, as many COTS platforms are designed for camera integration. The main drawback of the multirotor system stems from FAA requirements. These platforms require a pilot to be on site at all times which violates the autonomous requirement from the customer. Additionally, they are relatively expensive, as the cost of long endurance, heavy lift multirotors starts around $2,000 dollars.

Table 27: UAV Multirotor Pros and Cons

Pros	**Cons**
Flight endurance	High cost
Ease of integration	Requires human presence at all times
Reusability	Weather susceptability

Tethered Multirotor

To increase endurance even further, a tethered multirotor can be powered via a power cable rather than by battery. This poses a great advantage for the endurance component of the flight vehicle trade study. These platforms are often used for surveillance in military, police, and domestic applications. HoverFlyTech has developed several systems, one including a landing nest for autonomous landing. Other companies such as Elistair, have developed a system deployable in under a minute. Although the tethered UAV has existed in a grey area in the past in terms of FAA regulations, it now falls under the UAV category. Since a tethered multirotor also requires a pilot on site, it still violates the autonomous customer requirement.

Table 28: Tethered Multirotor Pros and Cons

Pros	**Cons**
Flight endurance	High cost
Ease of integration	Requires human presence at all times
Reusability	Weather susceptability

Camera

ZEPHIR 2.5

The ZEPHIR 2.5 camera by Photon Etc. has spectral capabilities superior to those needed. Its operational wavelengths range from 0.85 to 2.5 μm. Additionally, the ZEPHIR 2.5 is easy to integrate, as it can be controlled with MATLAB and/or LABVIEW, both of which are familiar to the team. However, this camera is unreasonable due to its price tag, poor resolution (320x256), and its weight of 5.73 lbs. The ZEPHIR 2.5 also draws 60 watts of power, which is astronomical compared to the power draw of every other component in the system.

Table 29: ZEPHIR 2.5 Pros and Cons

Pros	**Cons**
Large spectral range	High cost
	Heavy
	Low resolution
	High power draw

FLIR Duo Pro R

The FLIR Duo Pro R is a compact, light-weight camera with exceptional resolution and mid ranged FOV. The Duo can be controlled with MAVLink (Micro Air Vehicle Link) and operates at 10 watts of power. This makes it easy to integrate, control, and power. Additionally, FLIR cameras have an interesting capability in that they also take optical images with every IR image taken. This could prove useful in post processing to identify certain objects and/or anomalies. However, the price of the Duo is out of the team budget, and it does not have any of the wavelength capabilities required.

Table 30: FLIR Duo Pro Pros and Cons

Pros	**Cons**
Lightweight	Improper wavelengths
Optical capability	High cost
Ease of integration	

EO-2223 NIR

The EO-2223 NIR detects light in the near-infrared. Near-infrared is useful for detecting biomass, suggesting possible use in an agricultural setting. The EO-2223 has a resolution of 2048x1088, which equates to 2.3 mega pixels. With this higher resolution, a larger area can be imaged, making launches more cost efficient. The EO-2223 is within budget and also has lenses with focal lengths ranging from 1.8 mm to 50 mm, meeting the wavelength requirement.

Table 31: EO-2223 Pros and Cons

Pros	**Cons**
Lightweight	Only NIR wavelengths
High resolution	
Affordable	

Microcontroller

Raspberry Pi 4B
The Raspberry Pi 4B is a versatile and powerful board that is compatible with Python. The Pi has 4 GB of RAM, a 1.5 GHz processor, internet connectivity, an ethernet connection, 2 USB 3.0 ports, 2 USB 2.0 ports, and 40 GPIO pins. As such, it is a versatile board capable of receiving, processing, and sending large amounts of data.

Table 32: Raspberry Pi 4B Pros and Cons

Pros	**Cons**
High processing power	Higher cost
Versatile	Large power draw
Runs on Python	Gets very hot

Arduino Mega 2560
The Arduino Mega 2560 has 54 digital IO pins, 16 analog inputs, a 16 MHz processor, and 8 kB of RAM. This microcontroller has much less processing power and interfacing capabilities than the Pi, making it a less desirable option for the requirements of this project.

Table 33: Arduino Mega Pros and Cons

Pros	**Cons**
Cost efficient	Uses C
Experience with board	Only data transfer is through IO pins
Many IO pins	Low processing power

BeagleBone Black
The BeagleBone Black is a relatively low cost Linux based board. The microcontroller has a 1GHz processor, 512MB of RAM, 82 IO pins, ethernet connectivity, and a USB port. The device, although capable, does not have the highest processing speed available, and is limited on the number of non-IO pin ports.

Table 34: BeagleBone Black Pros and Cons

Pros	**Cons**
High processing power	Relatively expensive
Uses Python	
Many IO Pins and USB port	

Silicon Labs Pearl Gecko
The Pearl Gecko has an extremely low power draw, but limited computational power. The board has a 40MHz processor, 256kB of RAM, and 65 IO pins. Although the board's low power draw is an appealing aspect, given the duration of the mission, its lack of processing power is too large a drawback to justify the energy savings. This consideration is particularly important when given the relatively small power consumption the board will have relative to all other electronics in the mission.

Table 35: Pearl Gecko Pros and Cons

Pros	Cons
Extremely low power draw	Most expensive option
	Low processing power

Power Source

Lead Acid Batteries

Lead acid batteries are one of the most common battery options considered for this project. They are commonly used as car batteries, wheelchair batteries, and as the battery component of solar systems. They typically operate on shallow charge cycles, meaning they aren't designed for discharging past 50% of their total capacity. Lead acid batteries typically have very long charging times with moderate discharge rates.

Table 36: Lead Acid Battery Pros and Cons

Pros	Cons
Low cost	Very low lifetime
Large capacity	
Low self-discharge	

Lithium Polymer Batteries

Lithium polymer (Lipo) batteries are commonly used in RC vehicles such as RC planes, drones, and RC cars due to their high energy density. Unlike lead acid batteries, lithium polymer batteries are designed for full cycles, meaning they can be fully charged and discharged without degrading the battery. Lithium polymer batteries can go through a high number of charge cycles which gives them a good lifetime. However, charging must be done carefully. If the temperature of the battery exceeds a certain limit or the charging current is too high, then the battery can become damaged, catch fire, or even explode, which is a safety hazard.

Table 37: Lithium Polymer Pros and Cons

Pros	Cons
Long lifetime	High cost
High energy density	Charging requires great care
Low self-discharge	

Lithium Ion Batteries

Lithium ion batteries share many characteristics with lithium polymer batteries. They have a high energy density, fairly long lifetime, and are designed for full charge cycles. Lithium ion batteries are commonly found in laptops, cellphones, cameras and other small electronics. Much like lithium polymer batteries, lithium ion batteries require great care when charging.

Table 38: Lithium Ion Pros and Cons

Pros	**Cons**
Long lifetime	High cost
High energy density	Charging requires great care
Low self-discharge	Known for fire hazards

Nickel Metal Hydride Batteries

Nickel metal hydride batteries (NiMH) are commonly found in many power tools, older personal CD players, and some older RC vehicles. NiMH batteries have fairly high energy density, much more than lead acid batteries but less than a lipo or lithium ion battery. NiMH batteries also have a discharge rate which lies between lead acid and lithium ion batteries respective discharge rates. Unfortunately, NiMH batteries suffer from a loss of capacity over time. As NiMH batteries undergo full charge/discharge cycles, they experience crystal formation which decreases the battery's capacity.

Table 39: Nickel Metal Hydride Pros and Cons

Pros	**Cons**
Average lifetime	Significant loss of capacity over time
High energy density	High cost
Very compact	

Solar Panels with a Lead Acid Battery

Solar panels have the ability to eliminate any need of charging or swapping batteries during a operational period and drastically reduce the net battery capacity required for the maximum operational period. Solar panels also allow for the use of lead acid batteries as a viable power solution. Lead acid batteries alone are not designed for full charge/discharge cycles and would not last long if used that way. With solar panels, the system would be able to utilize lead acid batteries without discharging beyond 50% of the maximum capacity.

Table 40: Solar Panels with Lead Acid Battery Pros and Cons

Pros	**Cons**
Very long lifetime	Increased integration complexity
Low cost	Increased deployment complexity
Drastically decreases battery capacity required	Need to regulate to avoid overcharging

Communications

SPI Bus

A SPI bus[16] is a wired serial interface used for communication between integrated circuits. SPI interfaces are offered on both the Arduino and Raspberry Pi. On the Raspberry Pi, the SPI interface can achieve data rates of up to 125 Mbps, well in excess of what is required for this project.

A SPI bus functions over three interface lines, an interface line, a data line for data sent from the master to the slave, and a data line for data sent from the slave to the master. Data between the slave and master devices is full-duplex and requires synchronization to the master's time signal. While this ensures that the two circuits share the same time, when the distance between microcontrollers increases, so too does the time delay error of the time signal. This correspondingly impacts synchronization and causes a loss of functionality. While this time delay error can be overcome by feeding the slave clock's signal back to the master, it is not a trivial task to extend SPI communication over long distances.

Table 41: SPI Pros and Cons

Pros	Cons
High data rate	Difficult to extend over long distance
Ubiquitous architecture	Requires extensive knowledge of electronics
	High power requirements

Ethernet Loval Access Netowrk

An Ethernet Loval Access Netowrk (LAN)[17] enables communication between computers through direct connection with a standard ethernet cable. Ethernet connections are renowned for their fast speeds (50 Gbps) and reliable communication. However, the implementation of such a method would likely be difficult and require more time integrating than other COTS methods.

Table 42: Ethernet Local Access Network Pros and Cons

Pros	Cons
High data rate	Difficult to implement
Long distance capability	

Radio Communication

Radio Communication is an alternating current which supports point-to-point communication. Given the size and power constraints of this project, the maximum feasible data rate is up to 345 kbps operating at 2.4 GHz[18], approximately one-third of the preliminary data expectation. However, its small size, low power consumption, and ease of integration still make it a viable candidate for communication. Additionally, radio communication has a range of up to 30 miles with heritage in many industrial applications.

Table 43: 2.4 GHz Radio Pros and Cons

Pros	Cons
Reliable over long distances	Much smaller data rate than desired
Low power consumption	
Small footprint	

Wireless Local Access Network

Wireless Local Access Networks (WLAN)[19] enable devices to easily connect with each other through the use of a gateway such as a wireless router. WLAN is based on IEEE 802.11 standards which allows for an ad hoc mode, in which mobile units transmit peer-to-peer. WLANs allow for high data rate communication over distances in excess of 50 meters. Furthermore, its industrial heritage and small scale make it suitable for remote communication on a project where operating conditions will be less than ideal.

Table 44: WiFi Pros and Cons

Pros	Cons
Reliable over long distances	Costly equipment
Extremely high data rate	

RS-485
RS-485[20] is a differential serial communication method which uses a pair of wires for each signal, meaning for full-duplex communication four wires are required. For this method to work, both connected instruments must use the same software protocol which limits the available microcontrollers/instruments. RS-485 allows for balanced digital multipoint systems, while RS-422 can support only one driver per bus line. RS-485 also addresses RS-232's lack of immunity to noise allowing for it to transmit over lines in excess of 100 feet at speeds of up to 10 Mbps. The largest hurdle of RS-485 is the minimum level of knowledge necessary to successfully implement it is much larger than with other communication methods.

Table 45: RS-485 Pros and Cons

Pros	Cons
Reliable over long distances	Requires shared software protocol
High data rate	Requires extensive technical knowledge

Data Calibration

In-Situ Probes
The first method of moisture level measurement is that of in-situ probes that would physically be placed inside the field being observed. A sample in-situ probe features a variable resistance sensor, where the two prongs of the sensors are inserted into the testing ground. These exposed prongs will be used to measure the conductivity in the intermediate space from which moisture level data can be backed out (where generally the higher the conductivity, the more water present). The general pros and cons of in-situ probes are presented in the table below.

Table 46: In-Situ Probes Pros and Cons

Pros	Cons
High temporal resolution	Additional calibration required
High spatial resolution	Low field coverage
High accuracy	Slightly intrusive

Remote Sensing Imaging
The second method of moisture level measurement would be a form of external remote sensing by an established, reputable moisture level technique. One such example of this would be Black Swift Technologies' "soil moisture mapping with unmanned aircraft systems" based in Boulder, Colorado. This organization has developed an unmanned aircraft system (UAS) that is capable of flying over a desired field and determining its soil moisture content using an on-board passive microwave radiometer. The Black Swift UAS pros and cons are shown below.

Table 47: Remote Sensing Pros and Cons

Pros	**Cons**
High field coverage	Low spatial resolution
Non-intrusive	Low temporal resolution
Highly scalable	Administrative Difficulty

Dirt Samples
In addition to the calibration methods listed above, physical dirt samples may also be retrieved from the testing area. This method would involve physically digging up soil from the testing area, baking the soil sample, and comparing the dry weight of the soil sample against its wet weight. While being a highly intrusive, time consuming method, the primary advantages of this method stem from the high accuracy that these measurements could provide as well as the overall technical ease of the measurement technique.

Table 48: Dirt Samples Pros and Cons

Pros	**Cons**
Industry standard	Highly intrusive
Accurate measurements	Time consuming
Technically simple	

Tether Material

Nylon Rope
The first option for tether materials is nylon rope, which is a synthetic fiber. This material has the highest strength out of the most common flexible rope fibers, with a minimum failure strength of 1486 lbf for a 1/4 in. diameter rope, weighing at 0.016 lbm/ft. Nylon rope is resistant to UV rays and rot, which is important considering the application in this mission will be outdoors. A downside to using nylon rope is that it absorbs water, and loses strength when wet. Furthermore, it's high elasticity creates less stability for the flight vehicle and imaging system.

Table 49: Nylon Rope Pros and Cons

Pros	**Cons**
Lightweight and flexible	Absorbs water and loses 10-15% strength when wet
Highest strength of synthetic fiber ropes	High elasticity creates issues for image alignment
Resistant to UV rays, rot, and abrasion	

Polypropylene Fiber Rope
The next option for tethers is another synthetic fiber: polypropylene fiber rope. This is another flexible lightweight option, with a minimum failure strength of 1125 lbf for a 1/4 in. diameter rope, weighing at 0.01 lbm/ft. This makes it the most lightweight option. This material has minimal stretching and works well in wet environments as it absorbs very little water. That being said, polypropylene is not as strong as Nylon and also experiences deterioration from long exposure to UV rays.

Table 50: Polypropylene Rope Pros and Cons

Pros	**Cons**
Very lightweight and flexible	Not as strong as Nylon
Minimal stretching	Sunlight may cause deterioration
Works well in wet environments	

Wire Rope
Wire rope is another material that is being assessed. This is by far the strongest option, with a minimum failure strength of 5480 lbf for a 1/4 in. diameter rope. It is also the heaviest option, weighing at 0.11 lbm/ft. Wire rope is the most durable choice, is UV resistant, and is the least expensive. However, it is quite heavy, is subject to developing barbs when frayed, and can also rust and kink which affects the failure strength.

Table 51: Wire Rope Pros and Cons

Pros	**Cons**
Very strong and durable	Very heavy
Less expensive	Subject to developing barbs when frayed
UV resistant	Subject to rusting and kinks

Kevlar Cord
Kevlar cord is the final tethering material being considered. 1/4 in. diameter Kevlar cord has a ultimate tensile strength of 1200 lbf, weighing in at 0.016 lbm/ft. Unlike many nylon cords, Kevlar undergoes very minimal yielding under tensile loads. This will be useful to reduce any stretching of the tethers during flight testing. To prevent moisture or UV exposure from hindering the Kevlar cord, the team has selected a Kevlar cord that is coated with a Polyester jacket. The selected Kevlar cord has a diameter of 7/64 in. which has an ultimate tensile load of 590 lbf and weighs in at only 0.003 lbm/ft. Further analysis of this selection is shown in section 6.2 of this report.

Table 52: Kevlar Cord Pros and Cons

Pros	**Cons**
High Strength to weight	Absorbs moisture
High tensile strength	Difficult to cut
UV resistant	More expensive than other options

Environmental Sensors

Temperature, Humidity, Pressure

SparkFun Atmospheric Sensor Breakout - BME280
The SparkFun BME280 atmospheric sensor gives measurements of barometric pressure, temperature, and humidity. The breakout provides both SPI and I^2C protocol, with 10 interface pins including power, ground, and communications. The operational voltage is 3.3V and takes measurements at less than 1mA and idles less than 5µA. This sensor has a large temperature range of -40°F to 185°F, as well as a large pressure range of 30kPa to 110kPa under 30,000

ft. The pressure measurement has a relative accuracy of 12 Pa, while the altitude measurement is accurate to about 1 meter. The sensor is able to measure within 100% of the humidity range and is listed for $19.95.[33]

Table 53: BME280 Sensor Breakout Pros and Cons

Pros	**Cons**
I^2C & SPI communication	Medium cost
Large altitude range	Large relative accuracy
Large temperature & pressure range	
Small size	

SparkFun Humidity and Temperature Sensor Breakout - HIH6130
The SparkFun HIH6130 humidity and temperature sensor only gives measurements of temperature and humidity; it can only use I^2C protocol. The operational voltage is ranged between 2.3V and 5.5V and also takes measurements at less than 1mA and idles around .6µA. This sensor has a much smaller temperature range of 41°F to 122°F. The sensor is able to measure within 10 - 90% of the relative humidity; the sensor is one of the more expensive at $29.95.[34]

Table 54: HIH6130 Sensor Breakout Pros and Cons

Pros	**Cons**
Incredibly small	High cost
Variable operating voltage	I^2C protocol only
Large humidity range	Small temperature range
	Pressure not included

DHT22 Temperature-Humidity Sensor
The DHT22 is another sensor that is only able to measure temperature and humidity, but it is less expensive ($9.95) and is easy to integrate. The sensor has similar data ranges as the BME280: temperature range of -40°F to 185°F with accuracy ±1°F, and is able to measure within 100% of the humidity range with 2-5% accuracy. This sensor has a minimum sampling rate of two seconds which could be an issue if continuous data was needed.[35]

Table 55: DHT22 Sensor Pros and Cons

Pros	**Cons**
Low cost	Pressure not included
Large data ranges	Medium current draw

MPL3115A2 - I^2C Barometric Pressure/Altitude/Temperature Sensor
The MPL3115A2 sensor measures altitude using pressure and also measures temperature; it can only use I^2C protocol. The operational voltage is ranged between 2V and 3.6V. This sensor also has a large temperature range of -40°F to 185°F. The sensor is able to measure pressure from 50 to 110 kPa up to 30,000 ft with accuracy of 30 cm (1ft). The sensor is one of the cheapest at $9.95.[36]

Table 56: MPL3115A2 Sensor Breakout Pros and Cons

Pros	Cons
Low cost	Only I^2C protocol
Small altitude resolution	Medium pressure/altitude range
Built-in altimeter calculation	
Accurate temperature resolution	

Accelerometer, Gyro

SparkFun Triple Axis Accelerometer and Gyro Breakout - MPU-6050
SparkFun's MPU-6050 sensor contains a 3-axis accelerometer and a MEMS 3-axis gyroscope to measure acceleration and angular velocity in the X, Y, and Z directions. The MPU-6050 also includes a Digital Motion Processor (DMP) capable of processing 9-axis MotionFusion algorithms. This sensor uses I^2C communication with digital output in rotation matrix, quaternion, Euler Angle, or raw data format. The gyro range from ±250 to ±2000 dps (degrees per second), and accelerometer full scale range of ±2g to ±16g.[37]

Table 57: MPU-6050 Sensor Breakout Pros and Cons

Pros	Cons
Large range of g measurements	High cost
DMP	Only I^2C protocol
	Large gyro operating current

SparkFun IMU Breakout - MPU-9250
SparkFun's MPU-9250 sensor contains a 3-axis accelerometer and a MEMS 3-axis gyroscope to measure acceleration and angular velocity in the X, Y, and Z directions. This sensor also includes a second chip (AK8963) which features a 3-axis magnetometer. The MPU-9250 uses 16-bit Analog-to-Digital Converters (ADCs) for digitizing all nine axes, making it a very stable 9 Degrees of Freedom board.[38] This sensor uses I^2C communication. The gyro range is the same, from ±250 to ±2000 dps (degrees per second), and accelerometer full scale range of ±2g to ±16g. The board design is very small and is in a medium price range of $14.95.[38]

Table 58: MPU-9250 Sensor Breakout Pros and Cons

Pros	Cons
Large range of g measurements	Medium cost
16-bit ADC	Only I^2C protocol
Small board size	Large gyro operating current

SparkFun 6 Degrees of Freedom Breakout - LSM6DS3
SparkFun's LSM6DS3 has similar traits compared to the first two IMU's, the gyro range is from ±250 to ±2000 dps (degrees per second), and accelerometer full scale range of ±2g to ±16g. The LSM6DS3 is capable of reading accelerometer data up to 6.7kS/s and gyroscope data up to 1.7kS/s.[39] This sensor does not include a magnometer which constrains it to a 6 degrees of freedom breakout. The LSM6DS3 uses an 8kb FIFO buffer to momentarily store

data. This sensor can us SPI and I^2C communication protocol. The board design is very small and is in a small price range of $10.95.[39]

Table 59: LSM6DS3 Sensor Breakout Pros and Cons

Pros	Cons
SPI communication	Lower supply voltage
Low cost	
Lower power consumption	

Windspeed

Cup Anemometer
Cup anemometers are the most popular type of windspeed sensor. Cup anemometers are typically made up of three or four cups that rotate about a common axis. When the wind blows, the cups turn, and this rotation is converted into a wind velocity reading. The three-cup anemometer is prone to less error than the four-cup anemometer, and more sensitive to changes in wind speed. Cup anemometers are typically very rugged and durable, which make them an attractive option for high-altitude and long-duration flights. However, mechanical parts may be affected by cold temperatures and ice. Additionally, low measurements are not very well studied, and therefore may be unreliable.

Table 60: Cup Anemometer Pros and Cons

Pros	Cons
Very durable	Prone to freezing
Easily accessible	Does not provide directional wind information
Easy to work with	Low readings unreliable
Affordable	

Vane Anemometer
Vane anemometers function in a similar way to cup anemometers, but with the caveat that the sensors resemble windmill blades instead of cups. Additionally, the blade sensors are positioned perpendicular to the wind instead of tangential. Vane anemometers are also rugged and durable, and are capable of measuring very high wind speeds without being damaged. However, for most accurate readings, they must be positioned directly perpendicular to the wind direction, meaning they are impractical for uses where wind direction cannot be predicted or controlled.

Table 61: Vane Anemometer Pros and Cons

Pros	Cons
Very durable	Difficult to get accurate reading in unpredictable winds
Affordable	
Can measure very high wind speeds	

Hot Wire Anemometer
Hot wire anemometers are one of the most sensitive anemometers on the market. Their main feature is a wire that is electrically heated and cools as wind blows across it. The current required to keep the wire temperature constant

is measured and related to wind velocity. This option is attractive because there are no mechanical parts prone to failure. In addition, hot wire anemometers are extremely precise and much smaller in size than the other anemometers discussed in this section. However, they are expensive, can be damaged easily by particles in the air flow, and are not suitable for flows where temperature fluctuates rapidly.

Table 62: Hot Wire Anemometer Pros and Cons

Pros	**Cons**
Very sensitive and precise	Easily damaged
No rotating parts	Expensive
Small in size	Cannot detect rapid temperature changes

Pitot Tube Anemometer
Pitot tube anemometers function by measuring the pressure of moving air and converting it to wind speed using Bernoulli's equation. Like the hot wire anemometer, pitot tubes have no rotating parts. They are small and easy to implement into a system, but they also have the caveat that they must be pointed in the direction of wind speed for an accurate reading to be made. Like the cup anemometer, they are unreliable at low wind speeds.

Table 63: Pitot Tube Anemometer Pros and Cons

Pros	**Cons**
Small and easily integrated	Must be pointed into wind
No rotating parts	Unreliable at low wind speeds

Ultrasonic Anemometer
Ultrasonic anemometers are the most expensive and advanced of the anemometers considered in this section. An ultrasonic anemometer measures windspeed by emitting sonic pulses between two transducers and measuring the time the pulses take to cross the distance between them. Like the hot wire and pitot tube anemometers, the ultrasonic anemometer has no rotating parts. Unlike the mechanical anemometers, the ultrasonic anemometer is less likely to be subject to freezing. Because this type of anemometer is so precise, they are relatively hard to find and extremely expensive.

Table 64: Ultrasonic Anemometer Pros and Cons

Pros	**Cons**
Extremely precise	Extremely expensive
No rotating parts	Hard to find
Less subject to freezing	

Reference Points

Types of Reference Points
There are two categories of reference points that could be used for image alignment on this project, near-IR markers and visual markers. The pros and cons of each are outlined below.

Near-IR Markers
Near-IR markers will be visible to an IR camera that already detects near-IR wavelengths (wavelengths suitable for detecting water). To construct near IR markers, the team can purchase near-IR stickers and stick them to heavy plates that will be set on the ground. Near IR stickers can be purchased online for relatively low cost. The following image is of a 3"x5" IR sticker sold on empiretactical.org. In order to make to make a reference point visible from the instrument suite in flight, the reference point must take up at least one pixel of each image. Since a pixel must represent no more than a 7"x7" footprint on the ground, four of these 3"x5" squares are required to fill one pixel. At a price of $12/sticker, each reference point would cost roughly $48 to produce. This price is one of the more affordable options studied.

Table 65: Near IR Stickers Pros and Cons

Pros	**Cons**
Compatible with IR camera	Expensive compared to visible markers
Easy to work with	
Weather-resistant	

Visible Wavelength Markers
Visible wavelength markers are another option that could be used to align images in post-processing. Visible wavelength markers would be comprised of plates on the ground larger than 7"x7" painted with a distinctive color that could be picked out by a visible wavelength camera. These would be affordable (the cost of weather-proof paint) but would force the team to mount a visual camera on the instrument suite.

Table 66: Visible Wavelength Markers Pros and Cons

Pros	**Cons**
Very affordable	Requires a visible camera for detection
Easy to work with	
Weather-resistant	

Number of Reference Points
The higher the number of reference points, the more robust the algorithm will be and images will have more points to be aligned with. A minimum of three points is sought out so that regardless of rotation of the instrument suite, all images can be aligned. If less than three are used, the reference points will not guarantee unique and proper alignment of images. On the other hand, having more reference points adds to the complexity of setup and cost contribution of reference points. It makes most sense to have three reference points in order to keep the cost as low as possible while having enough points to align images in post-processing.

Placement of Reference Points
In order to place reference points so that all images taken in nominal weather conditions have a view on all three reference points, it is necessary to space the reference points close to the center of the FOV (i.e. close to the ground station). To account for image drift due to translational motion of the instrument suite, the reference points should be placed within a radius from the ground station of a quarter of the radius of the FOV. This is an estimated ratio calculated based off of 10 feet of translational drift at an altitude of 150 feet off the ground. In addition, the reference points should be spaced such that there is no possibility for misaligning images due to rotational mismatch.

Rapid Deflation Device

Active Electronic Pressure Release
This system would constantly monitor altitude based on either the pressure sensor or GPS sensor. If the altitude ever

increased beyond a certain margin of the desired altitude, a solenoid valve connected to the base of the balloon by pipe fitting would be supplied power. This power would cause the solenoid valve to open, releasing the gas stored inside the balloon. Ideally, the rate of release of this gas would be slow enough that the balloon would make a controlled descent to the surface.

Table 67: Active Electronic Pressure Release Pros and Cons

Pros	**Cons**
Controllable deflation	Moderately difficult implementation
Negligible leaking	
Low chance of accidental engagement	

This option boasts the fewest cons of any options presented. The only difficulty lies in the implementation, which involves pipe fittings and some electronics interfacing. This difficulty is outweighed by the benefits of this system, such as its reliance on an independent altitude sensor and low chance of accidental engagement.

Passive Mechanical Pressure Release

This system would be passive and involve no data monitoring. Connected to the base of the balloon by NPT fittings would be a safety pressure relief valve. These valves are designed to trip when the pressure goes above a certain threshold. In this case, the valve would be based on gauge pressure, taking the difference between the balloon interior and the environment. As the altitude increases, the gauge pressure would also increase due to a decrease in environmental pressure, causing the valve to open. Two types of these valves exist: the first releases pressure until a desired pressure is once again achieved. The second simply trips and releases all pressure. This group would use the second option. Similar to the solenoid, the valve chosen would ideally release pressure at a low enough mass flow rate to bring the balloon to the ground while still meeting FAA requirements.

Table 68: Passive Mechanical Pressure Release Pros and Cons

Pros	**Cons**
Controllable deflation	Often not accurate
No moving parts	Chance of leaking
	Moderately difficult implementation
	Higher chance of accidental engagement

This option is enticing due to its lack of moving parts, controllable deflation, and overall simplicity. Unfortunately, pressure relief valves within the budget of this project are wildly inconsistent. This inconsistency could place both the mission and users at risk if deflation is too rapid or occurs at the wrong time. For these reasons, this option was not further pursued.

Active Balloon Destruction Device

This method is the more aggressive of the three. It would involve a linear actuator pushing a sharp object into the surface of the balloon to pop it. This method would cause a *very* rapid deflation. The payload would then free fall to the surface.

Table 69: Active Balloon Destruction Device Pros and Cons

Pros	Cons
Very rapid deflation	Destroys balloon
Relatively simple implementation	Chance that balloon does not pop

This option is too costly and too dangerous for this project. Popping the balloon wastes an unacceptable amount of money. A freefalling payload, no matter how lightweight, is incredibly dangerous. In addition, there is a high chance this method fails to engage, resulting in the breaking of federal laws. For all of these reasons, this design will not be pursued further.

Ground Processor

Microcontroller

The first option for a ground processor would be a small single-board computer such as the microcontrollers studied for the airborne vehicle. One advantage of using such device would be the small physical size of the device, which would result in a much more compact ground-station design. However, with this compactness comes added design complexity. These devices will require additional interfaces for feasible user interface (i.e. a monitor and input devices) as well as additional devices for data storage.

Table 70: Ground Processor Microcontroller Pros and Cons

Pros	Cons
Small	Lower processing power
Inexpensive	Moderate implementation difficulty
Low power consumption	

Portable Computer

The second option would be to use a portable personal computer (such as laptop). In terms of processing power, user interface capabilities, and data storage, this option would be significantly more advantageous than a small single-board computer as it would be capable of handling these requirements without the addition of auxiliary interfaces. Although a laptop would be a relatively more expensive option, not only terms of monetary cost but also in terms operational power costs, it was deemed prudent to rely on a preexisting user interface than to build a custom user interface with a microcontroller. This group investigated laptops with an i5 core processor or better, such as the Lenovo Thinkpad T430.

Table 71: Ground Processor Portable Computer Pros and Cons

Pros	Cons
High Processing Power	High cost
Simple integration	High power consumption

References

[1] Nahon, M., "DYNAMICS AND CONTROL OF A NOVEL RADIO TELESCOPE ANTENNA." *Department of Mechanical Engineering, University of Victoria*, 1999.

[2] Johnson, A I., "Methods of Measuring Soil Moisture in the Field." *U.S. Geological Survey*, 1962.

[3] Jingheng Cheng, Xuemin Chen, Jing Li, Richard Liu, "Development of the RF soil moisture sensors," Proc. SPIE 6167, *Smart Structures and Materials 2006: Smart Sensor Monitoring Systems and Applications*, 2006.

[4] Hassan, L., "Topsoil moisture estimation for precision agriculture using unmmaned aerial vehicle multispectral imagery." *IEEE*, 2014.

[5] Sushko, A., "Advancements in low cost, long endurance, altitude controlled latex balloons." *IEEE Aerospace Conference*. 2017.

[6] Shih, Sun F., and Jonathan D. Jordan. "Use of Landsat Thermal-IR Data and GIS in Soil Moisture Assessment." *Journal of Irrigation and Drainage Engineering*, vol. 119, no. 5, 1993, pp. 868–879.

[7] AMS. "2.2 Megapixel machine vision CMOS image sensor" *CMOSIS CMV2000 data sheet*,

[8] H.Gowdad, Prasanna, et al. "Application of the Water-Related Spectral Reflectance Indices: A Review." Ecological Indicators, Elsevier, 31 Oct. 2018, *https://www.sciencedirect.com/science/article/abs/pii/S*1470160*X*18308215.

[9] Scherz, Paul, and Simon Monk. Practical Electronics for Inventors. 4th ed., McGraw Hill Education, 2016.

[10] California Institute of Technology, 2002, Spectral graph of soil, water, and grass. *https://www.e-education.psu.edu/natureofgeoinfo/c8_p5.html*

[11] U.S. Geological Survey, Landsat 8 wavelengths. *https://www.usgs.gov/faqs/what-are-best-landsat-spectral-bands-use-my-research?qt-news_science_products=3qt-news_science_products*

[12] Edmond Optics, EO-2223 Data Sheet, 21 Sep. 2019. *https://www.edmundoptics.com/p/eo-2223-nir-usb-30-camera/37394/*

[13] FLIR, FLIR Duo Pro R Data Sheet, 21 Sep. 2019. *https://www.oemcameras.com/uav-drone-components/flir-duo-pro-r.htm?gclid=EAIaIQobChMIvOfVmof65AIVMxh9Ch370QmdEAAYASAAEgIicPD_BwE*

[14] Photon etc etc, ZEPHIR 2.5, 21 Sep, 2019 *http://www.photonetc.com/zephir-25-HgCdTe*

[15] Sensors Unlimited, Micro-SWIR 640CSX, 21 Sep, 2019 *http://www.sensorsinc.com/products/detail/microswir−camera*

[16] Kugelstadt, Thomas. "Extending the SPI bus for long-distance communication." *Texas Instruments Incorporated.* 2011.

[17] "A Background on Power Over Ethernet (PoE, PoE+ Hi-PoE)." *Perle Systems Technical Notes*, *https://www.perle.com/supportfiles/poe_background_technical_note.shtml*

[18] "P2400: Miniature 2.4 GHz Wireless Modem." *Microhard Corporation.*

[19] Giuseppe Anastasi, Eleonora Borgia, Marco Conti, and Enrico Gregori. "IEEE 802.11 Ad Hoc Networks: Performance Measurements." *The Computer Society*. *https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber =* 1203643

[20] Manny Soltero, Jing Zhang, and Chris Cockril. "RS-422 and RS-485 Standards Overview and System Configurations." *Texas Instruments Incorporated.* June 2002.

[21] "10 Things to Know Before Buying Rope," *paracordgalaxy.com https://paracordgalaxy.com/content/*23 − 10 − *things* − *to* − *know* − *before* − *buying* − *rope*.

[22] "Nylon Rope," *ULINE*. $https://www.uline.com/BL\_3913/Nylon-Rope$.

[23] Rope, N., "The Advantages of Using Nylon Rope," *Quality Nylon Rope*. $https://www.qualitynylonrope.com/blog/advantages-of-using-nylon-rope/$.

[24] "Wire Rope - Strength," *Engineering ToolBox*. $https://www.engineeringtoolbox.com/wire-rope-strength-d\_1518.html$

[25] "Polypropylene Fiber Rope - Strength," *Engineering ToolBox*. $https://www.engineeringtoolbox.com/polypropylene-rope-strength-d\_1516.html$.

[26] "Nylon Rope - Strength," *Engineering ToolBox. https://www.engineeringtoolbox.com/nylon-rope-strength-d_1513.html.*

[27] "Exploring the Atmosphere with Weather Balloons." Exploring the Atmosphere with Weather Balloons, UCAR Center for Science Education, *https://scied.ucar.edu/weather-balloons.*

[28] US Department of Commerce, and NOAA. "Weather Balloons." National Weather Service, NOAA's National Weather Service, 23 Sept. 2015, $https://www.weather.gov/bmx/kidscorner_weatherballoons$.

[29] Rastogi, Nina Shen. "How Many Balloons Would It Take to Lift a House like the One in Pixar's Up?" Slate Magazine, Slate, 4 June 2009, *https://slate.com/news-and-politics/2009/06/how-many-balloons-would-it-take-to-lift-a-house-like-the-one-in-pixar-s-up.html.*

[30] An Introduction to Cluster Ballooning, *http://www.clusterballoon.org/intro/intro.html.*

[31] "How Much Does A Hot Air Balloon Cost?" Hot Air Flight, 26 Aug. 2018, *http://www.hotairflight.com/how-much-does-a-hot-air-balloon-cost/.*

[32] "Hot Air Balloons Classifieds" RSS, $http://www.hotairballooning.com/classified/categories/full_systems.html$.

[33] "SparkFun Atmospheric Sensor Breakout - BME280." SEN-13676 - SparkFun Electronics, *https://www.sparkfun.com/products/13676.*

[34] Hughey, Tim. "SparkFun Humidity and Temperature Sensor Breakout - HIH6130." SEN-11295 - SparkFun Electronics, *https://www.sparkfun.com/products/11295.*

[35] Adafruit Industries. "DHT22 Temperature-Humidity Sensor Extras." Adafruit Industries Blog RSS, *https://www.adafruit.com/product/385.*

[36] Adafruit Industries. "MPL3115A2 - I2C Barometric Pressure/Altitude/Temperature Sensor." Adafruit Industries Blog RSS, *https://www.adafruit.com/product/1893.*

[37] M, Doug. "SparkFun Triple Axis Accelerometer and Gyro Breakout - MPU-6050." SEN-11028 - SparkFun Electronics, *https://www.sparkfun.com/products/11028.*

[38] Steele, John. "SparkFun IMU Breakout - MPU-9250." SEN-13762 - SparkFun Electronics, *https://www.sparkfun.com/products/13762.*

[39] "SparkFun 6 Degrees of Freedom Breakout - LSM6DS3." SEN-13339 - SparkFun Electronics, *https://www.sparkfun.com/products/13339.*

[40] David, and Gavin, "Anemometer Buying Guide and the Types You Can Choose From." Weather Station Reviews, 9 June 2019, *https://weatherstationexpert.com/anemometer-buying-guide/.*

[41] "Buy R. M. Young 81000V, 3 Axis Ultrasonic Anemometer." MegaDepot.

[42] "Home." Cole, *https://www.coleparmer.com/i/digi-sense-mini-vane-anemometer-with-nist-traceable-calibration/*

[43] "STA2 - Fieldpiece STA2 - STA2, In Duct Hot-Wire Anemometer." *SupplyHouse.com*.

[44] PCE Americas Inc. “Pitot Tube Anemometer PCE-HVAC 2.” Pitot Tube Anemometer PCE-HVAC 2, PCE Instruments, 1 Oct. 2019.

[45] “Nichrome 80 Wire 16 AWG RW0384 - 25 Ft 2.96oz Resistance.” TEMCO Industrial, temcoindustrial.com/temco-rw0384-nichrome-80-wire-25-ft.html.

[46] “Nichrome 80 Wire 16 AWG RW0384 - 25 Ft 2.96oz Resistance.” TEMCO Industrial, temcoindustrial.com/temco-rw0384-nichrome-80-wire-25-ft.html.

[47] “3.7V 700mAh LiPo Battery Pack (Compatible with Syma X5, X5C, X5SC, X5SW and Cheerson CX-30W).” Tenergy Power, power.tenergy.com/3-7v-700mah-lipo-battery-pack-compatible-with-syma-x5-x5c-x5sc-x5sw-and-cheerson-cx-30w/.

[48] ”MOSFET Data Sheet”, https://cdn.sparkfun.com/datasheets/Components/General/FQP30N06L.pdf

[49] ”50 Watt .2 Ohm Resistor”, https://www.newark.com/caddock/mp850-0-20-1/power-resistor-non-inductive-50w/dp/11J1795

[50] Callister, William D., Rethwisch, David G. (2010). ”Materials Science and Engineering: An Introduction, 8th Edition”. Pg 129. John Wiley Sons, Inc.

[51] Balaram et. al. (2012). ”Inorganic Chemistry”. Pg 156. PHI Learning Private Limited.

[52] Van Amerongen, G. J. (1946). ”The Permeability of Different Rubbers to Gases and Its Relation to Diffusivity and Solubility”. Rubber-Foundation, Delft, Holland. https://doi.org/10.1063/1.1707667

[53] Emissivity Coefficients Materials. (n.d.). Retrieved from https://www.engineeringtoolbox.com/emissivity-coefficients-d447.html.

[54] https://www.engineeringtoolbox.com/friction-coefficients-d778.html

[55] https://www.engineersedge.com/coeffientsoffriction.htm